IN–SPACE PROPULSION: STRATEGIC CHOICES AND OPTIONS

HEARING

BEFORE THE

SUBCOMMITTEE ON SPACE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

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AN OVERVIEW OF THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION BUDGET FOR FISCAL YEAR 2018

THURSDAY, JUNE 29, 2017

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON SPACE,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to call, at 10:05 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Brian Babin [Chairman of the Subcommittee] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
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In-Space Propulsion: Strategic Choices and Options

Thursday, June 29, 2017
10:00 a.m.
2318 Rayburn House Office Building

Witnesses

Mr. William Gerstenmaier, Associate Administrator, Human Exploration and Operations Directorate, NASA

Mr. Stephen Jurczyk, Associate Administrator, Space Technology Mission Directorate, NASA

Dr. Mitchell Walker, Chair, Electric Propulsion Technical Committee, AIAA

Dr. Franklin Chang-Diaz, Founder and CEO, Ad Astra Rocket Company

Mr. Joe Cassady, Executive Director for Space, Washington Operations, Aerojet Rocketdyne

Dr. Anthony Pancotti, Director of Propulsion Research, MSNW

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON SPACE

Charter

TO:	Members, Committee on Science, Space, and Technology
FROM:	Majority Staff, Committee on Science, Space, and Technology
DATE:	June 29th, 2017
SUBJECT:	Space Subcommittee Hearing: "In-Space Propulsion: Strategic Choices and Options"

On Thursday, June 29th, 2017 at 10:00 a.m. in Room 2318 of the Rayburn House Office Building, the Committee on Science, Space, and Technology, Subcommittee on Space, will hold a hearing titled, "In-Space Propulsion: Strategic Choices and Options."

Hearing Purpose

NASA is pursuing several in-space propulsion technologies to advance not only human exploration, but also uncrewed spacecraft operations. The hearing will explore NASA's current portfolio of investments in in-space propulsion technologies, the state of the various technologies, and how they fit into future space architectures.

Witnesses

- **Mr. William Gerstenmaier**, Associate Administrator, Human Exploration and Operations Directorate, NASA
- **Mr. Stephen Jurczyk**, Associate Administrator, Space Technology Mission Directorate, NASA
- **Dr. Mitchell Walker**, Chair, Electric Propulsion Technical Committee, AIAA
- **Dr. Franklin Chang-Diaz**, Founder and CEO, Ad Astra Rocket Company
- **Mr. Joe Cassady**, Executive Director for Space, Washington Operations, Aerojet Rocketdyne
- **Dr. Anthony Pancotti**, Director of Propulsion Research, MSNW

Staff Contact

For questions related to the hearing, please contact Mr. Tom Hammond, Staff Director, Space Subcommittee, Mr. G. Ryan Faith, Professional Staff Member, Space Subcommittee, or Ms. Sara Ratliff, Policy Assistant, Space Subcommittee, at 202-225-6371.

Chairman BABIN. The Subcommittee on Space will now come to order. Without objection, the Chair is authorized to declare recesses of the Subcommittee at any time.

Welcome to today's hearing titled "In-Space Propulsion: Strategic Choices and Options." I would now like to recognize myself for five minutes for an opening statement.

We are on the cusp of a giant leap in space transportation technology. Advances in in-space propulsion systems hold the promise of radically altering space exploration. Breakthroughs will allow for faster travel, larger payloads, and greater efficiency. All of this will allow humanity to access the very farthest reaches of the solar system. This is clearly a subject that excites the imagination.

NASA has led the way in developing in-space propulsion since its inception. The Space Electric Rocket Test, or SERT–1, as well as the Deep Space 1 (DS1) and Dawn missions laid the foundation of electric propulsion. The Nuclear Engine for Rocket Vehicle Applications program, or NERVA, demonstrated the viability of nuclear thermal propulsion. These investments have ensured U.S. leadership in in-space propulsion, which is important for not only civil space missions, but also national security missions and commercial applications. Commercial in-space propulsion systems, operating at kilowatts of power, are a relatively mature technology today: In 2015 Boeing began offering the first all-electric commercial satellites.

Because of these successes, we stand on the threshold of a new era, one in which in-space propulsion and power systems could grow to a scale and sophistication that would support human spaceflight and exploration. NASA is currently developing in-space power and propulsion systems that are an order of magnitude more powerful than modern commercial systems. Originally developed for the cancelled asteroid retrieval mission, this system will now be appropriately incorporated into NASA's exploration architecture and may be used on NASA's Deep Space Gateway.

Similarly, developing this technology has taught us valuable lessons that will inform the next generation of in-space propulsion, which will send humans on to Mars. NASA's Human Exploration Mission Directorate is supporting research on three new in-space propulsion technologies. These systems operate at hundreds of kilowatts of power which is another ten times more powerful than the systems under development for use around the Moon, and could be used on a Deep Space Transport system for missions to Mars and even beyond.

The next-generation in-space propulsion technologies under development by three of today's witnesses will be critical to ensuring that the exploration of Mars is possible, sustainable, and affordable. I hope that their testimony can help the Committee better understand the unique mission options that each technology will offer.

As important as these developments are for the journey to Mars, the most exciting payoffs may come from the ability to develop these new engines even further. As discussed in NASA's Technology Roadmaps, scaling up the power levels another order of magnitude and building systems that will operate with thousands of kilowatts of power will significantly transform how humanity explores the solar system. These systems could even put the outer planets within reach of human explorers.

To be clear, these developments are not simply about human spaceflight; rather it is an across-the-board change in technology on par with the jump from sailing vessels and steam-powered ships. That long-term vision is still quite a ways off and will require further work, but the promise is utterly exciting.

Smart investments, focused exploration goals, and constancy of purpose will maintain U.S. leadership in not only in-space propulsion, but also space exploration more broadly.

Our witnesses today can help us better understand how all of these efforts fit together. I look forward to hearing about how in-space propulsion can expand our reach. Advancements in these technologies will literally open up a universe of possibilities.

[The prepared statement of Chairman Babin follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
June 29, 2017

Media Contact: Kristina Baum
(202) 225-6371

Statement of Space Subcommittee Chairman Brian Babin (R-Texas)
In-Space Propulsion: Strategic Choices and Options

Chairman Babin: We are on the cusp of a giant leap in space transportation technology. Advances in in-space propulsion systems hold the promise of radically altering space exploration. Breakthroughs will allow for faster travel, larger payloads, and greater efficiency. All of this will allow humanity to access the far reaches of the solar system. This is clearly a subject that excites the imagination.

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Our witnesses today can help us better understand how all of these efforts fit together. I look forward to hearing about how in-space propulsion can expand our reach. Advancements in these technologies will literally open up a universe of possibilities.

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Chairman BABIN. And I would now like to recognize the Ranking Member, the gentleman from California, for an opening statement.

Mr. BERA. Thank you, Mr. Chairman.

Chairman BABIN. I'm sorry. Can I——

Mr. BERA. Yes, please.

Chairman BABIN. I'm about to forget our Ranking Member of the full Committee. Sorry about that. Go ahead, Mr. Bera.

Mr. BERA. Although before I read my opening statement, I'm told that there's a group from the Society of Physics students here today, and I just want to recognize those students that are here in the audience because they're interning in a variety of places including our own House Science, Space, and Technology Committee, and you guys represent the future, and that's why we do what we do, so if you could stand up for a quick second so we can recognize all of you. Thank you for being here.

You know, Mr. Chairman, I think this is a very timely topic, and I'm looking across at this distinguished panel. It may take us a while to get through all of your statements but I think we're going to be well-educated.

You know, chemical propulsion remains a critical part of today's human exploration program. The two rocket boosters on NASA's Space Launch System use a solid chemical propellant and SLS's RS–25 core stage rockets utilize liquid chemical propellant. However, relying solely on chemical propulsion for deep space travel would result in spacecraft having to carry large amounts of propellant, possibly requiring multiple launches even before a mission can be initiated. That is why many experts believe that NASA will need advanced propulsion systems to power the agency's future robotic and manned spacecraft.

NASA is currently using non-chemical in-space propulsion in the form of electric propulsion. Electric propulsion is a continuous, low-thrust process and has been used by a few NASA robotic spacecraft, such as the Dawn probe, which has investigated the asteroid Vesta and is now orbiting Ceres.

The Department of Defense space vehicles and commercial satellites also make use of solar electric power, but primarily for orbit raising and repositioning. For example, each Advanced Extremely High Frequency Space Vehicle, which provides critical global communications to our warfighters, uses solar electric propulsion subsystems.

Another type of in-space propulsion enabled through the use of nuclear reactors was studied to a limited extent in the 1960s. However, engineers found that the amount of shielding needed to protect crew from the dangerous effects of prolonged exposure to radiation generated by the nuclear reactor as well as other technical difficulties were challenges that were hard to overcome at that time.

Now that we're planning on extended human travel into space, research into all forms of advanced propulsion technologies, including nuclear fission, is likely to intensify in the years ahead. It's critical that we find ways to reduce the time crew is exposed to galactic cosmic rays and other dangerous deep-space radiation. Significantly reducing mission duration times can only be achieved through advanced in-space propulsion.

As NASA continues to develop our plans on how to send humans to Mars and returning them safely to Earth, now is a good time to examine the present and future options for in-space propulsion.

Mr. Chairman, I look forward to hearing from our witnesses about different propulsion technologies and the unique characteristics that make them best suited to particular missions in space.

Thank you, and I yield back.

[The prepared statement of Mr. Bera follows:]

OPENING STATEMENT
Ranking Member Ami Bera (D-CA)
of the Subcommittee on Space

House Committee on Science, Space, and Technology
Subcommittee on Space
"In-Space Propulsion: Strategic Choices and Options"
June 29, 2017

Good morning. And welcome to our distinguished panel.

Thank you Mr. Chairman for calling this important hearing to look at ongoing developments in advanced in-space propulsion technologies.

Chemical propulsion remains a critical part of today's human exploration program. Indeed, the two rocket boosters on NASA's Space Launch System use a solid chemical propellant and SLS's RS-25 core stage rockets utilize liquid chemical propellant. However, relying solely on chemical propulsion for deep space travel would result in spacecraft having to carry large amounts of propellant, possibly requiring multiple launches even before a mission can be initiated. That is why many experts believe that NASA will need advanced propulsion systems to power the agency's future robotic and manned spacecraft.

NASA is currently using non-chemical in-space propulsion in the form of electric propulsion. Electric propulsion is a continuous, low thrust process and has been used by a few NASA robotic spacecraft, such as the Dawn probe which has investigated the asteroid Vesta and is now orbiting Ceres.

Department of Defense (DoD) space vehicles and commercial satellites also make use of solar electric power, but primarily for orbit raising and repositioning. For example, each Advanced Extremely High Frequency (AEHF) Space Vehicle, which provides critical global communications to our warfighters, uses solar electric propulsion subsystems.

Another type of in-space propulsion—enabled through the use of nuclear reactors—was studied to a limited extent in the 1960s. However, engineers found that the amount of shielding needed to protect crew from the dangerous effects of prolonged exposure to radiation generated by the nuclear reactor as well as other technical difficulties were challenges that were hard to overcome at that time.

With plans now focusing on extended human travel into space, research into all forms of advanced propulsion technologies, including nuclear fission, is likely to intensify in the years ahead. It's critical that we find ways to reduce the time crew is exposed to galactic cosmic rays and other dangerous deep-space radiation. Significantly reducing mission duration times can only be achieved through advanced in-space propulsion.

As NASA continues developing our plans on how to send humans to Mars and returning them safely to Earth, now is a good time to examine the present and future options for in-space propulsion. Mr. Chairman, I am looking forward to hearing from our witnesses about different propulsion technologies and the unique characteristics that make them best suited to particular missions in space.

Thank you and I yield back.

Chairman BABIN. Absolutely. Sorry about the confusion. Now the Ranking Member.

Ms. JOHNSON. Thank you very much. Let me say good morning to everyone and welcome our witnesses, and thank you, Mr. Chairman. I appreciate the opportunity to discuss in-space propulsion with a wide range of government, academic, and industry experts.

In-space propulsion will be a critical enabler of our future missions, especially those involving human exploration beyond Earth orbit, and I'm delighted that all of the young people of the future are here, and I hope that I see the enthusiasm as we have experienced in the past.

It is important that the Subcommittee assess the state of research and development related to in-space propulsion technologies, which NASA, the National Academies, and the NASA Advisory Council all consider a priority. Not only is this technology important for NASA and our space program, but it would also have benefits for the commercial sector, which already uses electric propulsion for maintaining commercial satellite positioning.

Mr. Chairman, I look forward to this hearing from our witnesses about the range and types of in-space propulsion technologies being studied and the progress of the research and development into each. When we consider progress, we also need to understand whether sufficient resources are being invested to make sure the technologies will be ready when NASA needs them. It is important to note that the budget for NASA's Space Technology Mission Directorate, which includes work on in-space propulsion, has been relatively flat. Can we achieve the milestones for the needed technology development on a flat budget?

Mr. Chairman, our investments in research and development of enabling technologies such as in-space propulsion are our seed corn for achieving our goals for space exploration. It is our job to ensure that we make the needed investments will yield us the kind of results we seek.

I thank you, and yield back.

[The prepared statement of Ms. Johnson follows:]

OPENING STATEMENT
Ranking Member Eddie Bernice Johnson (D-TX)

Committee on Science, Space, and Technology
Subcommittee on Space
"In-Space Propulsion: Strategic Choices and Options"
June 29, 2017

Good morning. And welcome to our witnesses. I look forward to your testimony.

Mr. Chairman, I appreciate the opportunity to discuss in-space propulsion with a wide range of government, academic, and industry experts. In-space propulsion will be a critical enabler of our future missions, especially those involving human exploration beyond Earth orbit. And it is important that the Subcommittee assess the state of research and development related to in-space propulsion technologies, which NASA, the National Academies, and the NASA Advisory Council all consider to be a priority. Not only is this technology important for NASA and our space program, but it would also have benefits for the commercial sector, which already uses electric propulsion for maintaining commercial satellite positioning.

Mr. Chairman, I am looking forward to hearing from our witnesses about the range and types of in-space propulsion technologies being studied and the progress of the research and development into each. When we consider progress, we also need to understand whether sufficient resources are being invested to make sure the technologies will be ready when NASA needs them. It is important to note that the budget for NASA's Space Technology Mission Directorate, which includes work on in-space propulsion, has been relatively flat. Can we achieve the milestones for the needed technology development on a flat budget?

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Thank you, and I yield back.

Chairman BABIN. Thank you.

Let me introduce our very distinguished panel of witnesses today. The first one I'd like to introduce is Mr. Bill Gerstenmaier, Associate Administrator of the Human Exploration and Operations Directorate at NASA. Mr. Gerstenmaier provides strategic direction for all aspects of NASA's human exploration of space and cross-agency space support functions including programmatic direction for the operation and utilization of the International Space Station. He holds a bachelor of science in aeronautical engineering from Purdue University, and a master of science in mechanical engineering from the University of Toledo. Welcome.

Next I'd like to introduce Mr. Stephen Jurczyk, our second witness today, Associate Administrator of the Space Technology Mission Directorate at NASA. As Associate Administrator, he manages and executes the space technology programs focusing on infusion into the agency's exploration and science mission needs, proving the capabilities needed of the greater aerospace community and developing the Nation's innovation economy. Mr. Jurczyk is a graduate of the University of Virginia, where he received a bachelor of science and a master of science in electrical engineering. We welcome you.

Our third witness today is Dr. Mitchell Walker. He is Chairman of the Electric Propulsion Technology Committee of the American Institute of Aeronautics and Astronautics. Dr. Walker is also a Professor of Aerospace Engineering at the Georgia Institute of Technology, where he directs the High Power Electric Propulsion Laboratory. From 2011 to 2012, Dr. Walker served on the National Research Council Aeronautics and Space Engineering Board for the Air Force reusable booster system study. His research interests include both experimental and theoretical studies of advanced plasma propulsion concepts for spacecraft and fundamental plasma physics. He also conducts research on Hall-effect thrusters, gridded ion engines, diagnostics for plasma interrogation and thruster characterization, and several other aspects of electric propulsion. He received his Ph.D. in aerospace engineering from the University of Michigan, where he specialized in experimental plasma physics and advanced space propulsion. We welcome you, Dr. Walker.

Fourthly is Dr. Franklin Chang-Diaz, Founder and CEO of Ad Astra Rocket Company. Dr. Chang-Diaz has flown a record seven space missions, logging over 1,600 hours in space including 19 hours on three separate spacewalks. In 1994, he founded and directed the Advanced Space Propulsion Laboratory at the Johnson Space Center where he continued developing propulsion technology. Prior to founding Ad Astra, Dr. Chang-Diaz joined the technical staff of the Charles Stark Draper Laboratory in Cambridge, Massachusetts, where he conducted research in fusion. He earned a bachelor of science in mechanical engineering from the University of Connecticut and his Ph.D. from MIT. We welcome you, Dr. Franklin Chang-Diaz.

Fifth is Mr. Joe Cassady, Executive Director for Space of Washington Operations for Aerojet Rocketdyne. Mr. Cassady has 33 years of experience in propulsion as well as mission and systems analysis. This includes flight projects for both the Air Force and NASA. He is also the Vice President of the Electric Rocket Propulsion Society. Mr. Cassady earned a bachelor's of science and a master's of science in aeronautics and astronautics from Purdue University. He also received a graduate certificate of systems engineering from George Washington University. We welcome you.

Our sixth witness today is Dr. Anthony Pancotti, Director of Propulsion Research at MSNW. Dr. Pancotti previously worked at the Air Force Research Laboratory at Edwards Air Force Base where he reviewed and investigated a range of advanced propulsion concepts. In 2011, he joined MSNW to work on a variety of fusion and propulsion and plasma concepts and is now the Principal Investigator for their Next Step Propulsion program. He earned his Ph.D. in aerospace engineering from the University of Southern California, where he designed, built and tested an experimental high-efficiency electrothermal ablative pulsed plasma thruster—that's a mouthful—called a capillary discharge.

I now recognize Mr. Gerstenmaier for five minutes to present his testimony.

TESTIMONY OF MR. WILLIAM GERSTENMAIER, ASSOCIATE ADMINISTRATOR, HUMAN EXPLORATION AND OPERATIONS DIRECTORATE, NASA

Mr. GERSTENMAIER. Thank you very much, Members of the Committee for the opportunity to be here to discuss in-space propulsion.

Propulsion is a critical element of any human exploration plan or architecture. We need to further develop the ability to move humans and cargo in space to expand human presence into the solar system. Electric propulsion can be a key enabler to successful missions and activities beyond the Earth-Moon system. It offers significant advantages over other forms of propulsion, most notably, efficiency. Electric propulsion can offer the ability to move large masses through space with minimum fuel usage. The other advantages are, the fuel is storable, does not boil off, and can be easily resupplied. However, the thrust level of current electric propulsion systems is typically low and it requires a significant amount of time to move the spacecraft in space. Even for habitats in the vicinity of the Moon, we are planning to use 12–1/2-kilowatt electric thrusters, which is about 5 kilowatts, or 40 percent, higher thrust than typical thrusters used today.

This disadvantage of long times is substantial when you're considering transporting crew. We prefer to transport crew as fast as possible to avoid prolonged exposure to microgravity and high radiation conditions. We anticipate the early systems for sending crew beyond the Earth-Moon system will use a combination of chemical and much higher thrust level electric propulsion systems, possibly 50 to 100 kilowatts or greater.

The future systems we are investigating would increase thrust level and shorten transit time while still maintaining the high efficiency. We are looking at increasing thrust levels by factors of 10. These systems are at lower technology readiness levels but offer the promise for new technologies in the future. We have partnered with American industry through our next step broad agency announcement including some of the panelists here today to investigate and advance the capabilities of these emerging systems.

Looking at a variety of systems in the early stage of development is important. Maturing technologies and demonstrating system performance through ground testing prior to committing to utilizing them and operational systems and beginning a major systems development activity helps constrain program costs and schedule risk. NASA and other R&D organizations have learned that starting systems development activities prematurely can lead to significant technical challenges and unacceptable cost and schedule growth. The broad agency analysis process allows us to investigate the specifics of systems design before committing to technologies into an actual spacecraft or system.

As we prepare for missions in the vicinity of the Moon and ultimately Mars, electric propulsion will be a key enabling technology. We will build off of the work done in support of the Asteroid Redirect Mission. Our ARM concept worked the tremendous benefits of electric propulsion for moving large masses in space, which transformed our approach for human exploration in deep space. The Asteroid Redirect Mission also helped us to understand the advantages of departing the Earth-Moon system for Mars from the vicinity of the Moon rather than from Earth orbit, and we believe using electric propulsion to preposition key large elements will be necessary for human Mars-class missions.

Electric propulsion will play a key role in emerging concepts such as crew-tended habitation modules in the vicinity of the Moon. With advanced electric propulsion, we will have the ability to move habitat systems to various orbits around the Moon. We can support crewed science operations from the module and various lunar orbits—equatorial, halo orbits, or even an orbit around Lagrangian point two on the far side of the Moon. This far-side lunar orbit location would allow telerobotic operations from crews onboard the habitat module on the far side of the Moon, something we—a region of the Moon we have never explored. The module is not stuck in one place around the Moon. It can be moved to various locations, thanks to electric propulsion.

As we look to electric propulsion for crew-tended habitation systems around the Moon, we will look for synergies with the commercial communications satellite industry and take advantage of electric spacecraft development in that market. Combining these capabilities with higher-power electric propulsion systems being developed by NASA's Space Technology Mission Directorate will enable both the advance of U.S. industrial capabilities and the creation of the in-space infrastructure we need in the lunar vicinity to further Nation's space exploration goals.

Electric propulsion and advanced propulsion systems will be a key enabler for human exploration systems of the future.

Thank you for the opportunity to discuss this topic with the Committee, and I look forward to your questions.

[The prepared statement of Mr. Gerstenmaier follows:]

HOLD FOR RELEASE
UNTIL PRESENTED
BY WITNESS
June 29, 2017

Statement of
Mr. William H. Gerstenmaier
Associate Administrator
Human Exploration and Operations Mission Directorate
and
Mr. Stephen Jurczyk
Association Administrator
Space Technology Mission Directorate
National Aeronautics and Space Administration

before the

Subcommittee on Space
Committee on Science, Space and Technology
U. S. House of Representatives

Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to appear before you today to discuss NASA's work on in-space propulsion systems that will take our astronauts into the solar system on missions of deep space exploration and will increase the capability and reduce the cost of science, commercial, and other Government missions. Validation of these and related capabilities, including the Space Launch System (SLS) and Orion, are necessary elements of NASA's planned deep space exploration architecture.

The Space Technology Mission Directorate (STMD) is developing capabilities for in-space propulsion, including cryogenic propellant storage, power generation and energy storage, and on-orbit refueling. High power solar electric propulsion (SEP) capabilities, scalable to handle power and thrust levels needed for deep space human exploration missions, are considered essential to efficiently and affordably perform human exploration missions to distant destinations such as Mars. In addition, NASA is investing in technologies that will allow for the in-space storage and transfer of cryogenic fuels to meet the needs for future propulsion stages to move crew from Low Earth Orbit to a variety of destinations. A key goal is to demonstrate these new capabilities in the next few years and infuse them into human missions in the next decade. STMD is working closely with the Human Exploration and Operations Mission Directorate's (HEOMD) Advanced Explorations Systems (AES) Division to incorporate and integrate new technologies and innovations as they are matured to the point of infusion.

Solar Electric Propulsion (SEP)

Solar Electric Propulsion (SEP) technology has long been a priority technology investment by STMD, and SEP has been of great interest to NASA and other Government organizations and industry for many years. The focus of the SEP technology project has been on lighter and more efficient solar array structures and electric thrusters including the electronics to power them (called a power processing unit or

PPU) that are about 2.5 times the power level of today's thrusters of that type. Recently, NASA demonstrated full performance compatibility of a high power electric propulsion thruster and power processing unit, with more than 2,500 total hours of testing. The Agency subsequently awarded a contract to Aerojet Rocketdyne for the development and delivery of engineering development units of a 13 kilowatt (kW) thruster and PPU by the end of 2018. Advanced solar arrays developed by NASA and industry partners through a NASA Research Announcement (Deployable Space Systems and Orbital ATK) are two times lighter and use four times less stowed volume for the same amount of electricity produced by commercially available arrays. Deployment of a Rollout Solar Array was recently demonstrated on the International Space Station. These are significant steps forward toward systems that can be utilized in the next few years for science missions, Mars exploration, and widespread use on vehicles in Earth orbit and in cislunar space. The solar array technology is already being utilized in commercial spacecraft designs, and similar adoption of the new electric thrusters is also expected because the new performance levels for both the arrays and thrusters were designed in collaboration with commercial space industry. As such, NASA could potentially become a marginal buyer of the technology in the future, thus lowering overall mission cost.

Lower-power SEP systems are available now and have been used for a variety of spacecraft over the last decade to manage station keeping and provide continuous thrust for deep space missions with the appropriate mission profile. For NASA, examples include Deep Space 1 and Dawn. The current SEP system being developed for a demonstration-class mission will provide between 30 and 50 kilowatts of power. The final objective system that HEOMD envisions for its deep space exploration missions involves a 300 kW system. STMD intends to develop the SEP technology components, as well as fund the integration and flight demonstration of a 30-kW-class high power SEP system. To permit the development of a 300 kW system, many technology elements – including advanced high power solar arrays, advanced high power thrusters and a new generation of power management and power processing systems – will be needed relative to current SEP capabilities. The main purpose of the 30 kW demonstration-class system is to develop, integrate and demonstrate these advanced component technologies to clearly validate extensibility to the 300 kW system. Such a 30 kW demonstration system can also be directly applied to science as well as Department of Defense (DoD) missions which are not feasible today. Furthermore, the component technologies, particularly the advanced solar arrays, will have direct commercial applicability to future communications satellites.

The SEP project illustrates the strength of a multi-customer approach to technology development. The long-term need for human exploration involves deploying a 300 kW SEP space tug for deep space missions. Meanwhile, both the commercial space sector and the Science Mission Directorate have shown interest in utilizing the component technologies – especially the deployable solar arrays at the 5 kW to 30 kW power levels. Commercial satellite firms will soon use these arrays, with their lower weight and improved packaging efficiency, to lower the cost of future communications satellites. As a result of the careful planning by STMD, an architectural pathway now exists that will evolve SEP from the limited capability available today all the way to a human-exploration-class system. Along the way, STMD will provide tremendous benefit to multiple customers including the commercial space industry.

The Asteroid Redirect Robotic Mission (ARRM) portion of the Asteroid Redirect Mission (ARM) made substantial steps towards developing a highly efficient, large scale SEP capability that will be needed in NASA's strategy to position future habitats, landers, and other elements in Mars orbit prior to a crewed mission, and possibly deliver crew to Mars on a vehicle that also uses chemical propulsion. The capability to move multi-ton objects in space, such as cargo for a Mars mission and support reliabilities needed for human-scale Mars missions, will be of critical importance as we prepare for deep space missions beyond the Earth-Moon system. The SEP system is an essential component to deliver cargo for Mars missions, logistics and potentially the propulsive return stage to Mars orbit – efficiently and affordably emplacing these assets prior to the arrival of humans.

Formulation of the ARRM is being closed out and a revised approach to early crewed missions in the lunar vicinity is emerging in NASA plans. Early missions are intended to build toward more extended duration, deeper space human missions. To support longer human stays beyond low-Earth orbit earlier than was possible with the ARRM, the same advanced SEP integrated capability could be used in this cis-lunar capability. Deployment of 30-50-kW-class SEP as an initial step would offer: a highly efficient power and propulsion capability to support longer duration human habitation, a platform for communications and other lunar vicinity services for extended crew presence, the ability to complete a needed integrated flight demonstration, and advance systems use aligned with emerging commercial and other Government needs. Our analyses of in-space orbit transfers in the lunar vicinity show a 5- to 15-fold savings of propellant for this system as compared to chemical-only systems.

In addition to these SEP investments, NASA is also evaluating the different generation of extremely high-power electric propulsion technologies that offer the potential for substantially reduced transit times to Mars and other deep space destinations. These technologies are in the early development stage, with several significant system development challenges that need to be addressed prior to being implemented on a NASA mission. The technologies being evaluated include the Variable Specific Impulse Magnetoplasma Rocket (VASIMR), a nested Hall thruster, and a Lorentz force thruster that are funded as part of the Next Space Technologies for Exploration Partnerships (NextSTEP).

NextSTEP – Advanced Propulsion

NASA's journey to deep space will include key partnerships with commercial industry for the development of advanced exploration systems. In an effort to stimulate deep space capability development across the aerospace industry, NASA released the NextSTEP Broad Agency Announcement in late 2014 and, in 2015, selected 12 projects to advance the development of necessary exploration capabilities – seven in habitation, three in propulsion, and two in small satellites. NASA has since entered into fixed-price contracts with the selectees. Through these public-private partnerships, NextSTEP partners will provide advanced concept studies and technology development projects in the areas of advanced propulsion, habitation systems, and small satellites.

Advanced propulsion technology will be necessary to power exploration into deeper space. Selected partners will further the development of high power electric propulsion (EP) systems in order to lay the ground work for future lifetime testing and eventual technology demonstration missions of the EP systems. Currently, a state of the art electric propulsion engine operates at 5 kW of power, and NASA hopes to eventually achieve an integrated system operating at 300 kW or greater. Partners will demonstrate electric propulsion systems with higher specific impulse, higher efficiency, and higher power for long-duration deep space transportation systems and look at capabilities that are beyond those previously considered.

- **Ad Astra Rocket Company of Webster, Texas** will use the NextSTEP award to develop and test an advanced version of its VASIMR engine, an advanced plasma space propulsion system. Plasma is an electrically charged gas that can be heated to extreme temperatures by radio waves and controlled and guided by strong magnetic fields. The magnetic field also insulates nearby structures so exhaust temperatures well beyond the melting point of materials can be achieved. In rocket propulsion, the higher the temperature of the exhaust gases, the higher their velocity and the higher the fuel efficiency. The engine will be equipped with technological advances for a longer test to demonstrate its new proprietary core design and thermal control subsystem and to better estimate component lifetime.

- **Aerojet Rocketdyne Inc. of Redmond, Washington** will use the NextSTEP award to complete the development on a Power Processing Unit that will convert the electrical power generated by a spacecraft's solar arrays into the power needed for its patented 250 kW multi-channel Nested Hall Thruster. A nested Hall thruster consists of concentric discharge channels that can be operated individually or in combination to produce variable power levels.

- **MSNW LLC of Redmond, Washington** plans to develop a thruster for high-power, exploration-class missions. MSNW LLC will also partner with the University of Washington to develop and test a propulsion system capable of operation from 100 to 300 kW power on both traditional propellants and propellants manufactured using resources available during a deep space mission to the Moon or Mars, minimizing the materials carried from Earth.

These selections were for technologies currently in early research and development, and the objective is to demonstrate integrated electric propulsion systems in ground tests operating at a power level of 100 kW for 100 continuous hours by 2018.

Nuclear Thermal Propulsion (NTP)

An AES project was initiated in 2012 to develop and test reactor fuel elements, a critical nuclear thermal propulsion (NTP) technology development challenge, leading to a recommendation by a joint Department of Energy (DOE) and NASA independent review board in early 2015 to have a primary focus for future fuel development on graphite composite type NTP fuel materials with a secondary focus on cermet materials. The project has also conducted preliminary nuclear rocket engine concept development and initial assessments of the affordability of nuclear ground test methods for NTP. In 2015, the project conducted more rigorous fuel element fabrication and testing of the composite fuel elements. In 2016-17, the project has been working with the DOE to incorporate enriched uranium into the selected material and fuel elements and eventually test active fuel element(s) in a reactor to investigate the effects of radiation on material performance. The NASA Marshall Space Flight Center (MSFC), in partnership with DOE, is leading this project, with the Glenn Research Center (GRC) also providing a significant support role. STMD is investing in development of NTP fuel elements based on low enriched uranium (LEU) enabled by advances in materials processing to support potential future NTP efforts. The project is also completing a feasibility and affordability study of a NTP engine system utilizing a LEU-based reactor. In addition, the project conducted studies regarding licensing for engine ground test activities, and completed preliminary concept design and system sizing of contained ground test facility. These studies will be used to determine the feasibility and cost of advancing NTP via development and testing of a ground demonstration system. STMD is also supporting NTP capabilities with the eCryo project that is advancing our ability to perform long-term in-space storage of liquid hydrogen, a required capability for NTP.

NASA does not expect to require advanced propulsion technologies such as NTP in the initial crewed missions to the Mars system. Other advanced propulsion technologies such as high-powered SEP or EP, combined with chemical systems, meet the needs of U.S. commercial aerospace industry while serving as the core capabilities for the initial in-space propulsion system for the Mars crewed missions.

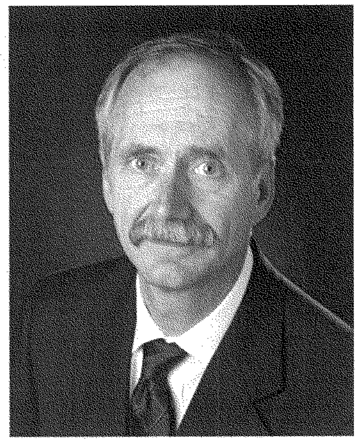
Additional Advanced Propulsion Investments

STMD is developing several additional in-space propulsion related technologies and advanced concepts. The Green Propellant Infusion Mission will conduct an in-space demonstration of a propulsion system using a propellant that is less toxic and has approximately 40 percent higher performance by volume than hydrazine, which will reduce spacecraft ground processing costs. NASA is also investing in several chemical and EP technologies for small spacecraft to enable future science and exploration missions utilizing cubesats and other small spacecraft. STMD's NASA Innovative Advanced Concepts program is also looking far into the future at revolutionary concepts to potentially enable interstellar robotic missions, such as directed energy propulsion for wafer-sized spacecraft and electric sail concepts that extract thrust from electrostatic repulsion of solar wind protons.

Conclusion

As NASA moves out beyond low-Earth orbit and into deep space, we will need to create a sustainable infrastructure to support the exploration of a variety of destinations in the decades ahead. One key component of this infrastructure is in-space propulsion, which will enable us to move crew and cargo across the vast distances involved in a timely manner. Beyond chemical propulsion (such as that used in the Space Launch System), NASA, along with private sector partners, are developing other options, including Solar Electric Propulsion. The development and demonstration of the advanced solar arrays and the Hall-thruster-based electric propulsion technologies are essential for efficiently performing future deep space human exploration missions, including Mars missions. Furthermore, advanced solar arrays and Hall thrusters have significant crosscutting utility to perform science missions, meet the needs of other Government agencies, and significantly improve the affordability and capability of our Nation's commercial satellites.

Mr. Chairman, we would be happy to respond to any questions you or the other Members of the Subcommittee may have.



WILLIAM H. GERSTENMAIER
ASSOCIATE ADMINISTRATOR FOR
HUMAN EXPLORATION AND OPERATIONS

William H. Gerstenmaier is the associate administrator for the Human Exploration and Operations Mission Directorate at NASA Headquarters in Washington, DC. In this position, Mr. Gerstenmaier provides strategic direction for all aspects of NASA's human exploration of space and cross-agency space support functions of space communications and space launch vehicles. He provides programmatic direction for the continued operation and utilization of the International Space Station, development of the Space Launch System and Orion spacecraft, and is providing strategic guidance and direction for the commercial crew and cargo programs that will provide logistics and crew transportation for the International Space Station.

Mr. Gerstenmaier began his NASA career in 1977 at the then Lewis Research Center in Cleveland, Ohio, performing aeronautical research. He was involved with the wind tunnel tests that were used to develop the calibration curves for the air data probes used during entry on the Space Shuttle.

Beginning in 1988, Mr. Gerstenmaier headed the Orbital Maneuvering Vehicle (OMV) Operations Office, Systems Division at the Johnson Space Center. He was responsible for all aspects of OMV operations at Johnson, including development of a ground control center and training facility for OMV, operations support to vehicle development, and personnel and procedures development to support OMV operations. Subsequently he headed the Space Shuttle/Space Station Freedom Assembly Operations Office, Operations Division. He was responsible for resolving technical assembly issues and developing assembly strategies.

Mr. Gerstenmaier also served as Shuttle/Mir Program operations manager. In this role, he was the primary interface to the Russian Space Agency for operational issues, negotiating all protocols used in support of operations during the Shuttle/Mir missions. In addition, he supported NASA 2 operations in Russia, from January through September 1996 including responsibility for daily activities, as well as the health and safety of the NASA crewmember on space station Mir. He scheduled science activities, public affairs activities, monitored Mir systems, and communicated with the NASA astronaut on Mir.

In 1998, Mr. Gerstenmaier was named manager, Space Shuttle Program Integration, responsible for the overall management, integration, and operations of the Space Shuttle Program. This included development and operations of all Space Shuttle elements, including the orbiter, external tank, solid rocket boosters, and Space Shuttle main engines, as well as the facilities required to support ground processing and flight operations.

In December 2000, Mr. Gerstenmaier was named deputy manager, International Space Station Program and two years later became manager. He was responsible for the day-to-day management, development, integration, and operation of the International Space Station. This included the design, manufacture, testing, and delivery of complex space flight hardware and software, and for its integration with the elements from the International Partners into a fully functional and operating International Space Station.

Named associate administrator for the Space Operations Mission Directorate in 2005, Mr. Gerstenmaier directed the safe completion of the last 21 Space Shuttle missions that witnessed assembly complete of the International Space Station. During this time, he provided programmatic direction for the integration and operation of the International Space Station, space communications, and space launch vehicles.

In 2011, Mr. Gerstenmaier was named to his current position as associate administrator for the Human Exploration and Operations Mission Directorate.

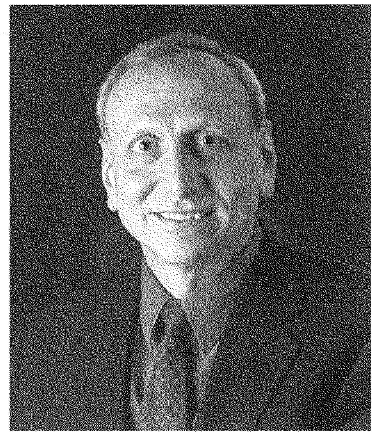
Mr. Gerstenmaier received a bachelor of science in aeronautical engineering from Purdue University in 1977 and a master of science degree in mechanical engineering from the University of Toledo in 1981. In 1992 and 1993, he completed course work for a doctorate in dynamics and control with emphasis in propulsion at Purdue University.

Mr. Gerstenmaier is the recipient of numerous awards, including three NASA Certificates of Commendation, two NASA Exceptional Service Medals, a Senior NASA Outstanding Leadership Medal, the Meritorious Executive Presidential Rank Award, and Distinguished Executive Presidential Rank Award. He also was honored with an Outstanding Aerospace Engineer Award from Purdue University. Additionally, he was twice honored by Aviation Week and Space Technology for outstanding achievement in the field of space. His other awards include: the AIAA International Cooperation Award; the National Space Club Astronautics Engineer Award; National Space Club Von Braun Award; the Federation of Galaxy Explorers Space Leadership Award; AIAA International Award; the AIAA Fellow; Purdue University Distinguished Alumni Award; and honored at Purdue as an Old Master in the Old Masters Program; recipient of the Rotary National Award for Space Achievement's National Space Trophy; Space Transportation Leadership Award; the AIAA von Braun Award for Excellence in Space Program Management; and the AIAA von Karman Lectureship in Astronautics.

He is married to the former Marsha Ann Johnson. They have two children.

October 2015

STEPHEN JURCZYK
ASSOCIATE ADMINISTRATOR FOR SPACE TECHNOLOGY



Mr. Stephen Jurczyk serves as Associate Administrator of the Space Technology Mission Directorate. As Associate Administrator, he manages and executes NASA's Space Technology programs, focusing on infusion into the agency's exploration and science mission needs, proving the capabilities needed by the greater aerospace community, and developing the nation's innovation economy.

Prior to this appointment, Mr. Jurczyk served as Deputy Director and then Director at NASA's Langley Research Center in Hampton, Va. Langley, founded in 1917, is the nation's first civilian aeronautical research facility and NASA's oldest field center. Jurczyk was appointed Deputy Director in 2005 and Director in 2014 overseeing research addressing such challenges as global climate change; affordable, safe deep space exploration; and improving the nation's air transportation system. As the senior management official at Langley, Jurczyk was responsible for the technical implementation of the center's aeronautical, space and science programs, as well as the overall management of the facilities valued at more than $3.3 billion and a workforce of over 3,600 engineers and scientists.

Jurczyk has spent most of his 25-year career in aerospace with NASA in various systems engineering, management, and senior leadership positions at NASA Headquarters, Langley, and NASA's Goddard Space Flight Center. He contributed to the development of several space-based remote sensing systems supporting earth science research including the Upper Atmosphere Research Satellite, Landsat 7, and the Clouds and Aerosol Lidar and Infrared Pathfinder Observations mission. As Director of Systems Engineering and later Director for Research and Technology at Langley, he led the organization's engineering contributions to many successful flight projects including the Mach 7 and 10 flights of the Hyper-X jet engine powered vehicle, the Shuttle Program return-to-flight, the successful flight test of the Ares 1-X vehicle, and flight test of the Orion Launch Abort System.

He is a recipient of the NASA Outstanding Leadership Medal and the Presidential Rank Awards of Meritorious and Distinguished Executive.

Jurczyk is a graduate of the University of Virginia where he received a Bachelor of Science and a Master of Science in Electrical Engineering.

Chairman BABIN. Thank you, Mr. Gerstenmaier.

Now I recognize Mr. Jurczyk for five minutes to present his testimony.

TESTIMONY OF MR. STEPHEN JURCZYK, ASSOCIATE ADMINISTRATOR, SPACE TECHNOLOGY MISSION DIRECTORATE,NASA

Mr. JURCZYK. Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, thank you for the opportunity to appear today to discuss NASA's in-space propulsion research and development activities with a focus on the agency's efforts in space technology.

NASA's Space Technology Mission Directorate—STMD—programs are aimed at key research and technology challenges that will enable more ambitious missions in the future and create a new space economy. STMD is developing new capabilities for in-space propulsion including higher-performing chemical propulsion, high-power electrical propulsion, and nuclear thermal propulsion. The goal is to demonstrate these new capabilities in the near term to transition them into robotic and human missions in the next decade.

Solar electric propulsion technology has long been a priority technology investment by STMD and such capabilities have been of great interest to NASA, other government organizations, and industry for many years. The focus of the current STMD technology project has been on increasing the solar power generation capability of spacecraft and development of advanced thrusters that are about two and a half times the power level of existing thrusters with significant increases in operational lifetime. Recently, NASA has demonstrated full performance of a high-power electric propulsion thruster system with more than 2,500 total hours of testing with no degradation in system performance. The agency subsequently awarded a contrast to Aerojet Rocketdyne for development and delivery of engineering units of a 12–1/2-kilowatt thruster system by the end of 2018.

The activities to advance solar power generation capability culminated in the successful development of advanced solar arrays by our industry partners, Deployable Space Systems and Orbital ATK, that are two times lighter and use four times less stowed volume for the same amount of electricity produced as compared to today's commercially available solar arrays.

NASA recently completed an Air Force Research Lab-sponsored test of the Deployable Space Systems Solar Array Technology on the ISS. The current STP system being developed for demonstration-class mission will provide between 300 and 500 kilowatts of power. The initial deep-space transport capability for crewed missions beyond the Earth-Moon system requires an approximately 300-kilowatt system. STMD intends to continue advancing thruster technology, increasing the power level up to 10 times current thruster systems to enable this capability.

The Solar Electric Propulsion Project illustrates the strength of a multi-application approach to technology development. Other government agencies and the commercial space sector have shown interest in utilizing the component technologies, especially the deployable solar arrays at 5 kilowatts to 30-kilowatt power levels. Commercial satellite firms will soon use these arrays with their lower weight and improved packaging efficiency to lower the cost of future communications satellites.

STMD is also currently in the second year of a three-year effort to develop a safe and affordable nuclear thermal propulsion system. This effort is focused on addressing the most significant challenges in developing an NTP system including reducing the risk and cost of the reactor system, enabling long-term storage of liquid hydrogen, the working fluid for NTP, and developing approach for safe ground testing of the system. The agency will use the results of these activities to determine the feasibility and cost of advancing NTP by development and testing of a ground demonstration system. Although NASA does not expect to require advanced propulsion technologies such as NTP in the initial crewed missions to the Mars system, NTP can reduce trip times to Mars significantly.

Finally, STMD will continue to advance power systems technologies to enable high-performing electric propulsion systems including both solar- and nuclear-based power generation.

Mr. Chairman, thank you for your support and that of this Committee. I would be pleased to respond to any of the questions that you or the other Members have.

Chairman BABIN. Thank you, Mr. Jurczyk.

I'd now like to recognize Dr. Walker for five minutes. Thank you.

TESTIMONY OF DR. MITCHELL WALKER, CHAIR, ELECTRIC PROPULSION TECHNICAL COMMITTEE, AIAA

Dr. WALKER. Mr. Chairman, Ranking Member Bera, and Members of the Subcommittee, thank you for the invitation to share my views on strategic investments in America's in-space propulsion technology program. I've been fortunate to serve on the faculty of the Daniel Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology since 2005. It gives me great pride to work closely with undergraduate and graduate students as they develop into the space propulsion engineers and scientists of our Nation's future.

I presently service as the Vice Chair of the American Institute of Aeronautics and Astronautics Technology Committee, an Associate Editor of the journal Spacecraft and Rockets, and the General Chair of the 2017 International Electric Propulsion Conference. I'm here today as an individual, and the views I express are mine alone.

Electric propulsion is the acceleration of propellant with electric energy to generate thrust for spacecraft. Hall-effect thrusters and gridded ion engines are successful examples of electric propulsion used in commercial, defense, and civil applications. Electric propulsion offers a significant advantage over chemical propulsion because the exhaust velocity is not limited by the amount of energy released from the chemical bonds of the propellant. Compared to chemical propulsion, the electrical approach enhances the efficiency of the propulsion system by more than an order of magnitude and leads to significant reductions in propellant mass. Typically, electric propulsion devices do not have large thrust because of the limited spacecraft power available.

NASA has been a leader in the development and flight of electric propulsion technology. NASA flew its first electric propulsion device in 1964. In 1998, the NSTAR ion propulsion system on NASA's Deep Space 1 spacecraft flew. The NSTAR ion engine enabled a trip that included fly-bys of an asteroid and a comet. In 2007, NASA launched the Dawn spacecraft that also uses NSTAR ion engine as primary propulsion. To date, Dawn has orbited both Ceres and Vesta. Scientists will continue to embrace the unique capabilities of electric propulsion to explore our solar system.

Our world has gradually shifted to a space-based infrastructure. That includes GPS, satellite radio, satellite TV, DOD communications, weather monitoring systems, and we stand in the midst of a paradigm shift in the requirements for these spacecraft from traditional chemical propulsion to electric propulsion. This shift is a result of a dramatic increase in available satellite electrical power. During the last 20 years, investments in solar array technology have increased geosynchronous satellite power from 1 kilowatt to over 25 kilowatts. In 2015, this trend culminated in the launch of Boeing's first all-electric spacecraft. All-electric satellites use electric propulsion as a primary propulsion and to provide 15 years of station keeping on orbit. The enormous propulsion mass savings achieved with electric propulsion allows two electric-satellites to launch on one smaller, less expensive launch vehicle. Current projections show that 50 to 75 percent of all future geostationary spacecraft will use electric propulsion.

All-electric spacecraft coupled with low-cost launch vehicles enabled our Nation to recapture the global launch vehicle market for commercial satellites. To remain economically competitive with this success, all launch vehicle providers are forced to upgrade their systems. In addition, Europe and Russia continue significant investments in electric propulsion. India and China each launched their first electrically propelled geostationary satellite this year. Japan is scheduled to launch its first all-electric commercial satellite in 2021. Electric propulsion is recognized as a competitive factor in the technology portfolios of these countries.

There are three activities that I strongly believe will bolster our Nation's leading position in electric propulsion technology. First, investments are required in electric propulsion technology across a spectrum of expected time to return on investment. Second, the Nation must invest in ground-based test facilities to develop and then fly the next generation of electric propulsion devices. Third, NASA must maintain a steady steering of investment in university research programs to ensure that the unique intellectual talent required to fly these systems is available when we are ready to execute on these ambitious missions.

The role of electric propulsion in the exploration of our solar system, economy and security will increase in the coming decades. Thus, investment in NASA's electric propulsion program helps maintain our leading position in space technology, aids economic competitiveness of our Nation, enhances our understanding of the physical world, and inspires current and future generations to pursue STEM careers.

Thank you for the opportunity to be here today. I look forward to your questions.

[The prepared statement of Dr. Walker follows:]

Written Statement of
Dr. Mitchell L. R. Walker
Georgia Institute of Technology
to the
Subcommittee on Space
Committee on Science, Space, and Technology
United States House of Representatives
on
In-Space Propulsion: Strategic Choices and Options
June 29, 2017

Mr. Chairman, Ranking Member Bera, and members of the Subcommittee, thank you for the honor of appearing before you today to discuss strategic investments in in-space propulsion technology. My name is Mitchell L. R. Walker. The views I express today are shaped by a 17-year aerospace engineering career. For the past 12 years, I have been fortunate to serve on the faculty of the Daniel Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. As director of Georgia Tech's High-Power Electric Propulsion Laboratory, I lead an active research and educational program focused on experimental and theoretical studies of advanced plasma propulsion concepts for spacecraft and fundamental plasma physics. The hands-on skills in experimental in-space propulsion being developed by the undergraduate and graduate students at Georgia Tech are of significant interest to NASA, the Office of Naval Research, the U.S. Air Force, DARPA, industry, and others in academia. It gives me great pride to work closely with these students, as they develop into the space propulsion engineers and scientists of our nation's future.

I presently serve as the vice chair of the American Institute of Aeronautics and Astronautics Electric Propulsion Technical Committee, an associate editor of the *Journal of Spacecraft and Rockets*, and the general chair of the 2017 International Electric Propulsion Conference. I am here today as an individual and the views I express are mine alone.

U.S. Leadership in Electric Propulsion

Electric propulsion is the acceleration of propellant with electrical energy to generate thrust for spacecraft. In the case of solar electric propulsion (SEP), the electrical energy is supplied by solar arrays on the spacecraft. Hall effect thrusters and gridded ion engines are successful examples of electric propulsion technology used in commercial, defense, and civil applications. Electric propulsion offers a significant advantage over chemical rockets because the exhaust velocity is not limited by the amount of energy released from the chemical bonds of the propellant. Compared to chemical propulsion, this approach enhances the efficiency of the thruster by more than an order of magnitude and leads to significant mass reductions – a change that allows us to include more payload mass on the same launch vehicle. Thus, electric propulsion systems enable space missions that could never take place with chemical propulsion alone. In spite of the fact that electric propulsion systems have large exhaust velocities, they do not have large thrust levels because of the limited available spacecraft power.

NASA has been a leader in the development and flight of electric propulsion technology since its introduction in the late 1950s. NASA flew its first electric propulsion device in 1964 as part of the Space Electric Rocket Test 1. In 1998, the NASA Solar Technology Application Readiness (NSTAR) ion propulsion system flew on the Deep Space 1 spacecraft. It marked the first use of electric propulsion as the primary propulsion system on a NASA mission. The NSTAR ion engine enabled a 163-million-mile trip that included flybys of the asteroid Braille and the comet Borelly. In 2007, NASA launched the DAWN spacecraft that also uses the NSTAR ion engines as primary propulsion. To date, DAWN has orbited both Ceres and Vesta, protoplanets in the asteroid belt between Mars and Jupiter. NASA's continuous investment in electric propulsion across the last 20+ years has made the U.S. the world leader in electric propulsion technology. One can only imagine the knowledge that will be created as scientists embrace the unique capabilities of this technology for future exploration of the solar system.

Paradigm Shift

Inspired by new technologies, our world has gradually shifted to a space-based infrastructure – one where space is a commodity. Modern infrastructure include GPS, satellite radio, satellite TV, cellphone backhaul, DoD communications, and weather monitoring systems. Earth imaging, a new generation of space service enabled by miniaturization of electronics and low-cost access to space, has also emerged. Companies such as Google/Terra Bella and Planet Labs sell near continuous imaging of most locations on Earth. The images will have a tremendous impact on commerce, agriculture, natural resources, and the stock market. The success and advantages of electric propulsion has not gone unnoticed by Earth-centric satellite operations.

We stand in the midst of a paradigm shift in the propulsion system requirements of satellites and deep space probes from traditional chemical propulsion to electric propulsion. This shift is the result of dramatic increase in satellite available power for payloads. During the last 20 years, investments in solar array technology have increased geosynchronous satellite power from approximately 1 kW to over 25 kW. As available power climbed, electric propulsion transitioned from an efficient technology used to perform stationkeeping to the primary propulsion system. In 2015, this trend culminated in the launch of Boeing's first all-electric commercial satellites. All-electric satellites use electric propulsion to perform the transfer maneuver from geostationary transfer orbit (GTO) to geostationary orbit (GEO) and provide 15 years of stationkeeping for applications such as DirecTV and military communications. Electric propulsion uses the existing solar power system on the satellite during the orbit transfer before the payload is in use. The enormous propellant mass savings allows two all-electric satellites to launch on a smaller, less expensive launch vehicle. The ability of electric propulsion to perform orbit raising as well as stationkeeping maneuvers has virtually eliminated the need for in-space chemical propulsion in many applications. Current projections show that 50-75 percent of all future geostationary satellites will use electric propulsion technology because of its ability to deliver the same service or capability as chemical propulsion at a significantly lower cost. In parallel, high-power EP devices are a core theme of NASA's technology roadmap.

The enabling performance and resultant competitive advantage of electric propulsion technology are appreciated around the world. The introduction of all-electric spacecraft coupled with the low-cost Falcon 9 launch vehicle enabled our nation to recapture the global launch vehicle market for commercial satellites. To remain economically competitive with this success, launch vehicle providers are forced to upgrade their systems. Competitiors in this market include the Ariane 6 of Europe, the Proton of Russia, the H3 of Japan, and the new Geosynchronous Satellite Launch Vehicle (GSLV) of India. The global response is not limited to launch vehicle providers. Europe has made significant investments in electric propulsion technology for both commercial satellites and science missions. Russia is building on its historic success in the electric propulsion field. China launched its first electrically-propelled geostationary satellite (a gridded ion engine, SJ-13) in April 2017. India launched its first electrically-propelled satellite (a Hall effect thruster, GSAT-9) in May 2017. Japan is actively developing a Hall effect thruster for its all-electric commercial satellite schedule to launch in 2021. All of these countries are establishing their presence in the global space communications and exploration markets using electric propulsion technologies. In addition, multiple countries, including Brazil and Turkey, have initiated electric propulsion research programs. The importance of electric propulsion in their technology portfolios cannot be overstated. It is a recognized factor in their competitiveness.

There are three activities that I strongly believe will bolster our nation's leading position in electric propulsion technology. First, investments are required in electric propulsion technology across the spectrum of expected time to return on investment. Second, the nation must invest in ground-based test facilities to develop and then fly the next generation of high-power electric propulsion devices. Third, NASA must maintain a steady stream of investment in university research programs to ensure that the intellectual talent required to fly high-power electric propulsion systems exists when the nation is ready to execute on these ambitious missions.

Investment Spectrum

Investments are required in the development of electric propulsion technology across the spectrum of expected time to return on investment. This approach ensures a robust technology development pipeline and inspires younger generations of scientists and engineers.

Near-term Investments

In the near term, the performance of electric propulsion is well aligned with many valuable NASA science missions, all-electric geostationary commercial satellites, and DoD communication satellite requirements. The U.S. commercial satellite industry faces strong international competition from Russia, China, India, Japan, and Europe. Investment in electric propulsion technology below 15 kW has a valuable immediate return on investment to the nation for exploration and science as well as to enhance competitiveness in the commercial satellite market. In particular, the low level of thrust provided by electric propulsion at current satellite power levels yields multiple month orbit transfers. To reduce the transfer time, significant increases are required in the operating power and performance (thrust-to-power ratio) of electric propulsion devices, but the thrust-to-power ratio of contemporary electric propulsion devices has plateaued. We must continue to invest in electric propulsion device thrust-to-power ratio to reduce orbit transfer times. Our international competition will seize this opportunity if we do not. Thus, aligning NASA investment with opportunities in industry will enable our nation to lead the "next" electric propulsion market.

Mid-term Investments

New upcoming mission demands will require significant propulsion system performance, but possibly in a different operational regime. As a sign of the promise and impact of electric propulsion, both OneWeb (initial investors include Airbus, Coca Cola, and Intelsat) and SpaceX have baselined Hall effect thrusters to maintain the operational orbit of their constellations. Electric propulsion will be part of the solution to our growing space debris challenge. To date, all envisioned solutions for removing objects from valuable orbits and require efficient propulsion systems. The low thrust, highly tunable performance of electric propulsion enables multiple sciences missions. The unprecedented GOCE mission (2009) used electric propulsion to balance the drag force experienced by the spacecraft. This enabled scientists to completely map the gravity field of the Earth. This knowledge is broadly used for to geodesy, oceanography, solid-earth physics, and has advanced our understanding of water location as a function of season. Electric propulsion enables precise control over spacecraft position and orientation for planetary scale studies of predicted physical phenomena, e.g., gravitational waves predicted by Einstein's theory of general relativity in 1915. The capability and flexibility of electric propulsion will be leveraged to address new upcoming mission demands.

Long-term Investments

The electrical power of spacecraft will continue to increase with advances in photovoltaics, deployable structures, and battery technology. At some time in the future, we will have the ability to fly spacecraft with several hundred kilowatts of power available on orbit. One application for this class of spacecraft is the delivery of supplies to Mars to prepare for the eventual arrival of humans. Note, multiple studies show that we can place humans on the surface of Mars with chemical propulsion. The efficiency of electric propulsion dramatically reduces the amount of propellant and number of launch vehicles required to deliver hardware to Mars. These reductions have significant financial advantages. There are at least two intermediate power flight demonstrations required as we move from 5-kW electric propulsion systems to the desired 100+ kW systems envisioned in NASA's future.

As a point of reference, NASA demonstrated a 100-kW gridded ion engine electric propulsion system in 1962. NASA immediately realized that the real issue was available electrical power. Thus, it is insufficient to merely consider the performance of the thruster, one must consider the performance of the propulsion system. This fact highlights the need to make a parallel investment in high-performance electrical power generation in space if we seek to fly high-power electric propulsion devices.

Facilities

The low thrust level of electric propulsion at available on-orbit power levels requires the technology to operate flawlessly for years to enable a successful mission. To generate this level of understanding and reliability requires extensive research and development testing in ground-based vacuum facilities. Unlike chemical propulsion, electric propulsion operation is unique because it accelerates individual particles. Thus, it is sensitive to the operating pressure within the vacuum facility. Second, the ground-based vacuum facility required to operate EP devices has a non-negligible impact on the performance and operation of EP devices. Above a certain pressure, the background gas can change the exhaust plume and alter the physical processes within the thruster. This physical process is a significant issue in ground-based facilities that must remove propellant as quickly as enters the facility from the thruster. Thus, the success of electric propulsion hinges on our ability to accurately predict the performance of the devices in ground-based vacuum facilities. To maintain the vacuum of space in ground-based facilities while the thruster is operating requires extensive pumps that can remove the propellant from the facility at the same rate that it is exhausted from the thruster.

The impact of the vacuum facility on EP device operation may be exacerbated as the required power level of EP devices continues to grow. Many national vacuum facilities are physically large enough to test thrusters at powers levels up to 100 kW, but their pumping speeds must be increased by at least an order of magnitude to avoid facility pressure effects for performance characterization, plume interaction studies, and life testing.

As a point of reference, the NSTAR ion engine that propelled Deep Space 1 and currently propels the DAWN mission has a nominal operation power of 2.3 kW. The gridded ion engines that compose the XIPS on Boeing spacecraft and the Hall effect thrusters on Lockheed Martin spacecraft possess nominal operating power slightly less than 5 kW. The capabilities of existing ground-based test facilities are well aligned for these devices. Investments are required to upgrade facilities to enable high-fidelity characterization of the near-term electric propulsion devices that will operate at nearly 15 kW. This infrastructure investment is required within the next 10 years for the U.S. to maintain its leading position in the in-space propulsion market. As we extrapolate this trend farther into the future, the nation must make the investment in several facilities (upgraded and new) to operation 100-kW class electric propulsion devices of the next generation of electric propulsion test facilities. This investment should be informed by a thorough optimization study of the number of facilities, their capability, and location. These investments are critical to NextSTEP thruster development.

Workforce Development

The long-term success of high-power electric propulsion requires a continuous investment in university research programs to ensure that the talent is available to develop and qualify these systems. Development programs such as NextSTEP electric propulsion systems provide a grand vision that excites and inspires students. The NASA Space Technology Research Fellowship is a critical support structure in the existing talent portfolio pipeline. The unprecedented demand for talent in electric propulsion from the Department of Defense and industry absorbs the vast majority of the graduates produced by the university with electric propulsion research programs. To attract and retain vibrant, talented students in high-power electric propulsion requires NASA to remain visibly active in this technology. We must sustain or develop the human capital required to develop and fly next-generation EP devices in the 2030 time frame and beyond.

Summary

The efficiency, reliability, and flexibility of propulsion systems impact our ability to explore and monetize space. Electric propulsion technology is advantageous in all these dimensions. The role of electric propulsion in the exploration of our solar system, economy, and security will increase in the coming decades.

First, investments are required in electric propulsion technology across the spectrum of expected time to return on investment. Near-term investment aligned with commercial spacecraft help U.S. industry retain a leading position in the global space industry. Mid-term investments will allow us to tackle the new mission requirements of smallsats, space debris, and planetary-scale investigations of fundamental physics. Second, the nation must invest in ground-based test facilities to develop and then fly the next generation of high-power electric propulsion devices. Third, NASA must maintain a steady stream of investment in university research programs to ensure that the intellectual talent required to fly high-power electric propulsion systems exists when the nation is ready to execute on these ambitious missions.

Investments in NASA's electric propulsion program aids the economic competitiveness our nation, enhances our understanding of the physical world, and inspire current and future generations to pursue STEM careers. This testimony includes examples of the impact of electric propulsion on the global economy and our ability to make scientific discoveries. It also demonstrates our nation's leading position in space technology.

BIOGRAPHY

Mitchell L. R. Walker is a Professor of Aerospace Engineering at the Georgia Institute of Technology where he directs the High-Power Electric Propulsion Laboratory. His primary research interests include both experimental and theoretical studies of advanced plasma propulsion concepts for spacecraft and fundamental plasma physics. Dr. Walker received his Ph.D. in Aerospace Engineering from the University of Michigan, where he specialized in experimental plasma physics and advanced space propulsion. His training includes rotations at Lockheed Martin and NASA Glenn Research Center. In 2005, he founded the electric propulsion program at the Georgia Institute of Technology. Dr. Walker has served as an Associate Editor of the American Institute of Aeronautics and Astronautics (AIAA) and on the Editorial Board of Frontiers in Physics and Astronomy and Space Sciences – Plasma Physics since 2015. He was a participant in the 2014 US National Academy of Engineering US Frontiers of Engineering Symposium and in 2015 he was the co-organizer for a focus session at the symposium. Dr. Walker is also a recipient of the AIAA Lawrence Sperry Award (2010), the Air Force Office of Scientific Research Young Investigator Program Award (2006), and a a NASA Faculty Fellow Award (2005). He is an Associate Fellow of the AIAA and serves as the incoming Chair of the AIAA Electric Propulsion Technical Committee. Dr. Walker served on the National Research Council Aeronautics and Space Engineering Board for the Air Force Reusable Booster System Study (2011-2012). His service to the American Physical Society's Division of Plasma Physics includes Local Coordinator of the Conference (2015) and Chair of the Subcommittee for Low Temperature and Dusty Plasmas (2016). Dr. Walker's research activities include Hall effect thrusters, gridded ion engines, magnetoplasmadynamic thrusters, diagnostics for plasma interrogation and thruster characterization, vacuum facility effects, helicon plasma sources, plasma-material interactions, and electron emission from carbon nanotubes. He has authored more than 100 journal articles and conference papers in the fields of electric propulsion and plasma physics.

Chairman BABIN. Thank you, Dr. Walker.
I'd now like to recognize Dr. Chang-Diaz for five minutes.

**TESTIMONY OF DR. FRANKLIN CHANG–DIAZ,
FOUNDER AND CEO,
AD ASTRA ROCKET COMPANY**

Dr. CHANG-DIAZ. Thank you, Mr. Chairman and distinguished Members of the Subcommittee. I am honored to be called to testify before you on this important topic for our Nation and for our civilization.

In securing our ability to travel in deep space safely and sustainably, we are also ensuring, or helping to ensure the survival of our species. I believe that space travel actually beckons humanity a lot more today than it did 50 years ago. But we need to secure a safe and robust and fast means of transportation. Going to the Moon is one thing; going to Mars is a completely different thing.

So on the screen I wanted to put up that graphic representation of the in-space propulsion challenge before us. Despite decades of progress in many areas of space technology, the challenges of deep-space transportation remain as clear and present as they were in the 1960s. Our transportation workhorse, the chemical rocket, has reached an exquisite level of refinement but it has also reached its performance limit. That technology will not provide us with a sustainable path to deep space. It does not mean that we need to discard it. On the contrary, chemical rockets will continue to provide foundational launch and landing capabilities for the foreseeable future and reducing their cost is a worthy goal.

But once you're in space, the path to sustainable transportation lies in high-power electric propulsion, and by high power, I mean power levels of 100 kilowatts and up. A hundred kilowatts is roughly the power of a small car. Three hundred kilowatts is the power of an SUV, just to give you a sense for what these things means.

Each one of us in the NextSTEP Program is due to demonstrate the efficient operation of our respective technologies at a power level of no less than 100 kilowatts for 100 continuous hours. These rockets will first be solar electric and later, as we move outwards from the sun, they must transition to nuclear electric power.

Ad Astra Rocket Company is an American corporation, developing a uniquely American technology. We are based in Texas. Our flagship project is the VASIMR engine. It is an electric rocket that fits squarely within the high-power niche as previously defined and can scale naturally to multi megawatts. The VASIMR originated at MIT in the 1980s. The technology was transferred to NASA in the 1990s and privatized in 2005 by Ad Astra Rocket Company in 2005. The most advanced VASIMR engine is the VX–200, which is a 200-kilowatt engine which has executed more than 10,000 reliable and efficient firings at power levels of 200 kilowatts and higher. Its performance data has been well vetted by the science community and published in the top peer-reviewed journals of our industry. The technology readiness level of the VASIMR is now between four and five. The lion's share of this development has been achieved at Ad Astra Rocket Company with more than $30M of private investment from U.S. and international investors.

In 2015, NASA became a partner and awarded us a three-year, $3-million-per-year NextSTEP contract to help bring the technology to TRL–5. We are halfway through this program and moving smartly to its successful completion in mid-2018.

Mr. Chairman and Members of the Subcommittee, our Nation as we move to explore deep space with humans, we must be able to travel fast to reduce the debilitating effects of space on the human body, to reduce the burden of consumables, life support, to be less constrained by planetary alignments and tight launch windows and to expand our capability to recover from unforeseen contingencies en route. In short, this is the problem punch list we still need to solve to give our astronauts a fighting chance in deep space. The development of high-power electric propulsion is critical to checking these boxes and to meeting our Nation's goals in space, and I look forward to your questions. Thank you very much.

[The prepared statement of Dr. Chang-Diaz follows:]

Statement by Dr. Franklin Chang Díaz
CEO, Ad Astra Rocket Company
For the Committee on Science Space and Technology,
Subcommittee on Space
U.S. House of Representatives

June 29, 2017

In-Space Propulsion: Strategies, Choices and Options

Mr. Chairman and distinguished members of the subcommittee, I am honored to be called to testify before you on this important topic for our nation and for our civilization. In securing our ability to travel in deep space safely and sustainably we are also insuring the survival of our species.

We have learned a lot about living and working in space during more than half a century of human space flight. We have also discovered many new things about our solar system and the universe in which we live. Every year we seem to find a handful more planets orbiting nearby stars, some of which may harbor the conditions for life as we know it. Even closer to home, the ocean worlds in our own solar system orbiting Jupiter and Saturn may offer the conditions for life. We have also opened the path for the private sector to usher new business opportunities on a cosmic scale for the United States. We are in the lead today but that leadership is by no means assured; we have to continue to earn it. Fortunately, Americans love competition.

I believe space travel beckons humanity even more today than it did 50 years ago, but we need to secure a safe, robust and fast means of transportation.

On the screen, I would like to offer you a graphic representation of the in-space propulsion challenge before us (display Figure 1).

Despite decades of progress in many areas of space technology, the challenges of deep space transportation remain as clear and present as they were in the 1960s. Our transportation workhorse, the chemical rocket, has reached an exquisite level of refinement. It has also reached its performance limit. That technology will not provide us with a sustainable path to deep space. It does not mean we need to discard it. On the contrary, chemical rockets will continue to provide foundational launch and landing capabilities for the foreseeable future and reducing their cost is a worthy goal.

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Mr. Chairman and members of the subcommittee, as our nation moves to explore deep space with humans we must be able to travel fast, to reduce the debilitating effects of space on the human body, to reduce the burden of consumables, life support, to be less constrained by planetary alignments and tight launch windows and to expand our capability to recover from unforeseen contingencies enroute. In short, this is the problem punch-list we still need to solve to give our astronauts a fighting chance in deep space. The development of high power electric propulsion is critical to checking these boxes and to meeting our nation's goals in space.

Thank you and I am happy to take your questions.

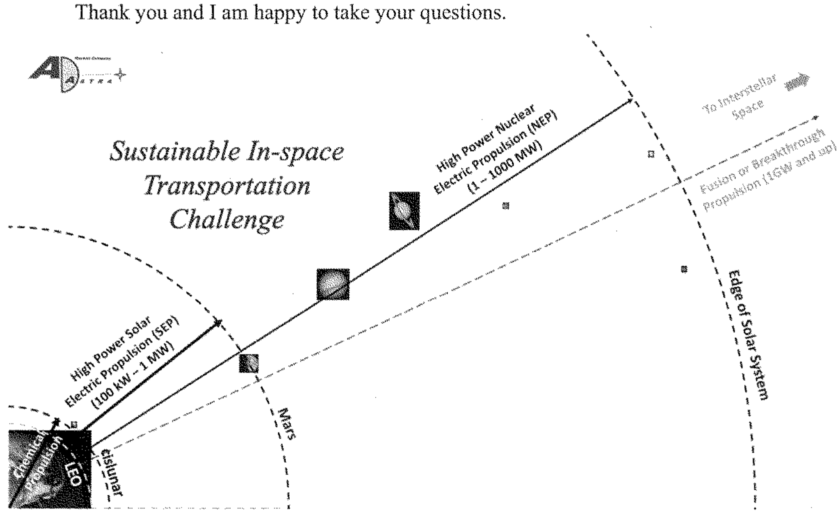


Figure 1

(end of opening statement)

Additional material submitted for the record

The VASIMR® engine works with plasma, an electrically charged gas that can be heated with electrical power to extreme temperatures (2-3 million degrees) by radio waves and controlled and guided by strong magnetic fields. The magnetic field also insulates the rocket casing from the hot plasma. In rocket propulsion, high exhaust temperature leads to high exhaust velocity and hence high fuel efficiency. Plasma rockets have exhaust velocities 10x greater than conventional rockets, so their propellant consumption is extremely low. The high efficiency allows a range of missions that are not possible with conventional chemical rockets.

Other important features of the VASIMR® engine include:

- Scalable from ~50 kW to multi-MW in a single engine
- Electrodeless design, implies long component life
- Multiple, low cost, abundant propellants, such as argon (~$5/kg) and krypton (~$300/kg), as compared with other electric thrusters, which operate with rare and expensive xenon (~$1000/kg).
- Variable thrust and specific impulse, can "shift gears" to better adapt to the gravity "hills and flats" of the mission.

Potential applications

The VASIMR® engine could provide primary propulsion for robotic SEP and eventually NEP spacecraft in many venues, with more capability and economy than chemical rockets. Examples:

1. A commercial multiuse solar-electric space tug for orbital debris mitigation, satellite support and cislunar cargo transport.
2. Drag compensation or reboost of orbital space stations in low Earth Orbit (LEO)
3. The VASIMR® engine could propel a re-usable high-power solar electric propulsion (SEP) deep-space catapult to deploy robotic missions to the Jupiter and Saturn systems faster than conventional rockets.
4. With advanced nuclear electric power, the VASIMR® engine provides nuclear electric propulsion (NEP), enabling fast (less than 90 days) human Mars transfers. These reduce radiation exposure and other space-induced debilitating effects on humans. It also relaxes the departure windows on NASA's Design Reference Architecture 5.0 (DRA-5.0) (see Fig 2).

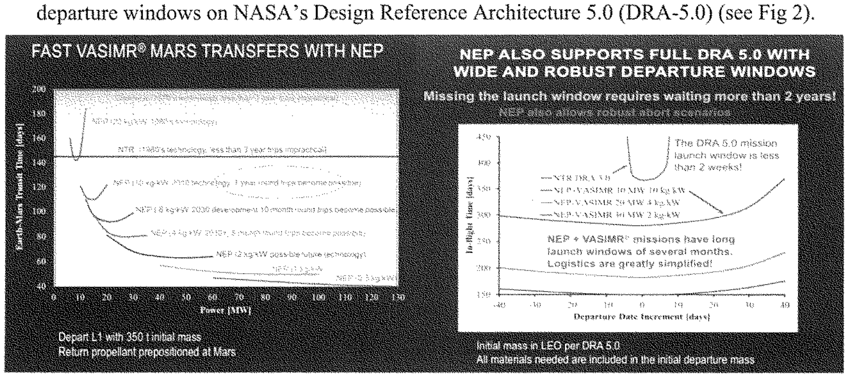
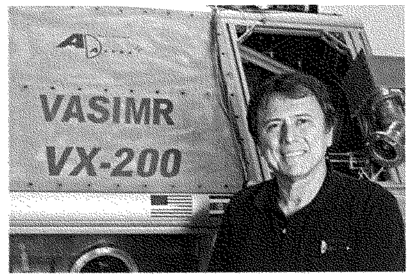


Figure 2

Dr. Franklin R. Chang Díaz

Chairman and CEO, Ad Astra Rocket Company



Dr. Franklin R. Chang Díaz

Franklin Chang Díaz was born April 5, 1950, in San José, Costa Rica, to the late Mr. Ramón A. Chang Morales and Mrs. María Eugenia Díaz Romero. At the age of 18, having completed his secondary education at Colegio de La Salle in Costa Rica, he left his family for the United States to pursue his dream of becoming a rocket scientist and an astronaut.

Arriving in Hartford Connecticut in the fall of 1968 with $50 dollars in his pocket and speaking no English, he stayed with relatives, enrolled at Hartford Public High School where he learned English and graduated again in the spring of 1969. That year he also earned a scholarship to the University of Connecticut.

While his formal college training led him to a BS in Mechanical Engineering, his four years as a student research assistant at the university's physics laboratories provided him with his early skills as an experimental physicist. Engineering and physics were his passion but also the correct skill mix for his chosen career in space. However, two important events affected his path after graduation: the early cancellation of the Apollo Moon program, which left thousands of space engineers out of work, eliminating opportunities in that field and the global energy crisis, resulting from the l973 oil embargo by the Organization of Petroleum Exporting Countries (OPEC). The latter provided a boost to new research in energy.

Confident that things would ultimately change at NASA, he entered graduate school at MIT in the field of plasma physics and controlled fusion. His research involved him heavily in the US Controlled Thermonuclear Fusion Program, managed then by the US Atomic Energy Commission. His doctoral thesis studied the conceptual design and operation of future reactors, capable of harnessing fusion power. He received his doctorate degree in 1977 and in that same year, he became a US citizen.

After MIT, Dr. Chang Díaz joined the technical staff of the Charles Stark Draper Laboratory in Cambridge, MA, where he continued his research in fusion. In that year, the Space Shuttle Enterprise made its first successful atmospheric test flight and re-energized the moribund US Space Program. Following this success, in 1977, NASA issued a nationwide call for a new group of astronauts for the Space Shuttle Program. In addition to US citizenship and in contrast to earlier such announcements in the 1960s, the qualification requirements also included an advanced scientific degree. Dr. Chang Díaz was ready.

Rejected on his first application to the Astronaut Program in 1977, he tried again in a second call in 1979. This time, successfully, becoming, in May of 1980, one of 19 astronaut candidates selected by NASA from a pool of more than 3,000 applicants and the first naturalized citizen from Latin America to be so chosen.

While undergoing astronaut training, Dr. Chang Díaz supported functions at the Johnson and Kennedy space centers and served as capsule communicator (CAPCOM) in Houston's Mission Control. In 1985 he led the astronaut shuttle support team at the Kennedy Space Center. During his training, Dr. Chang Díaz logged over 1,800 hours of atmospheric flight time, including 1,500 hours in high performance jet aircraft.

Dr. Chang Díaz achieved his dream of space flight on January 12, 1986 on board the Space Shuttle Columbia on mission STS 61-C. The 6-day mission deployed the SATCOM KU satellite and conducted multiple scientific experiments. After 96 orbits of the Earth, Columbia made a successful night landing at Edwards Air Force Base in California's Mohave dessert.

After a nearly 3-year hiatus, following the Challenger disaster of January 28, 1986, Dr. Chang Díaz flew a (world) record 6 more space missions, which contributed to major US space accomplishments, including the successful deployment of the Galileo spacecraft to Jupiter, the operation of the Alpha Magnetic Spectrometer, a major international particle physics experiment, the first and last missions of the US-Russian Shuttle-MIR Program and, on three separate space walks, totaling more than 19 hours outside the spacecraft, Dr. Chang Díaz led the installation of major components of the International Space Station (ISS) and conducted critical repairs on the Canadian ISS Robotic Arm. In his seven space missions, Dr. Chang Díaz logged over 1,600 hours in space.

Alongside with his astronaut duties, Dr. Chang Díaz continued his research in applied plasma physics, investigating applications to rocket propulsion. His 1979 concept of a plasma rocket became the VASIMR® plasma engine, embodied in 3 NASA patents to his name. In 1994, he founded and directed the Advanced Space Propulsion Laboratory (ASPL) at the Johnson Space Center where he managed a multi-center research team to develop this propulsion technology.

On July 8, 2005, after 25 years of government service, Dr. Chang Díaz retired from NASA to continue his work on the VASIMR® through the private sector. He is founder and current Chairman and CEO of Ad Astra Rocket Company, www.adastrarocket.com, a US private firm based in Houston Texas where the VASIMR® engine is being brought to space flight readiness in partnership with NASA. The company is also developing clean energy applications and hydrogen technology at its subsidiary in Guanacaste, Costa Rica.

Dr. Chang Díaz serves on the Board of Directors of Cummins Inc., a global power leader headquartered in Columbus, Indiana, and EARTH University, an international sustainable development educational institution in Costa Rica. He also leads the "Strategy for the XXI Century" http://www.estrategia.cr/, a master plan, aimed to transform Costa Rica into a fully developed nation by the year 2050.

In 1986, Dr. Chang Díaz received The Liberty Medal from President Ronald Reagan at the Statue of Liberty Centennial Celebration in New York City. He is a four-time recipient of NASA's Distinguished Service Medal, the agency's highest honor and was inducted in the US Astronaut Hall of Fame on May 4, 2012. He holds many honorary doctorates from universities in the United States and Latin America and has continued to serve in academia as an Adjunct Professor of Physics at Rice University and the University of Houston. He is married to the former Peggy Marguerite Stafford of Alexandria, Louisiana and has four daughters: Jean Elizabeth (43) Sonia Rosa (39), Lidia Aurora (29) and Miranda Karina (21). He enjoys music, flying and scuba-diving. His mother, brothers and sisters still reside in Costa Rica.

Published autobiographies

Dr. Chang Díaz has published two autobiographies:

"***Los Primeros Años***" http://www.adastrarocket.com/BookCover.jpg (ISBN 978-9968-47-133-6, first edition, ISBN 9789930519974, second edition) written in Spanish, covers his early childhood and adolescence, growing up in the 1950s and 1960s in Venezuela and Costa Rica where he forms his dreams of space exploration.

"***Dream's Journey***" http://www.adastrarocket.com/BookCover2.jpg (ISBN 978-0-692-33042-5), written in English, Dr. Chang Díaz embarks on a journey to that dream, alone, as an 18-year old immigrant, with $50 dollars in his pocket and a one-way ticket to the Land of Opportunity. His American journey unfolds against the backdrop of the tumultuous 1970s and takes him through a decade of adventure and discovery to the pinnacle of scientific achievement.

"***To Mars and Beyond, Fast!***" http://www.springer.com/us/book/9783319229171 written in English, Makes the case for high power electric plasma propulsion as a paradigm shift needed to establish a robust and sustainable human presence in deep space. The book covers a nearly 40-year journey in the development of the VASIMR® plasma engine, from first concepts to the current state of the technology as it is readied for its long duration performance tests at the Ad Astra Rocket Company in Texas.

These books are available directly from the publisher or by writing to: corporate@adastrarocket.com

June, 2017

Chairman BABIN. Thank you, Dr. Chang-Diaz.

I now recognize Mr. Cassaday for five minutes for your testimony.

TESTIMONY OF MR. JOE CASSADY, EXECUTIVE DIRECTOR FOR SPACE, WASHINGTON OPERATIONS, AEROJET ROCKETDYNE

Mr. CASSADY. Good morning. Chairman Babin, Ranking Member Bera, Members of the Committee and your staff, I appreciate the opportunity to be here this morning to discuss how in-space propulsion will enable and enhance the Nation's space exploration efforts together with the Space Launch System and the Orion.

I'm going to summarize my remarks here but I'd like to request that the written testimony be included in its entirety in the record. Thank you, sir.

On behalf of all Aerojet Rocketdyne employees across the country, I'd like to thank you and your Committee here for the relentless work the Members and staff have put forth to ensure that the Nation's space program is a success. Your commitment to exploration and discovery should be lauded.

This is a time of excitement and inspiration within the space community and, for that matter, across the country and around the world. We are building today the systems necessary to get humankind back to deep space and onto Mars starting in the early 2020s with the Deep Space Gateway in lunar orbit.

Just for a moment I'd like to tell you a little bit about who we are. Aerojet Rocketdyne is a world leader in power and propulsion. We've supported the Nation's defense, civil and commercial space efforts for over 70 years. Among the accomplishments we take pride in are having launched every astronaut from U.S. soil, landing seven spacecraft successfully on the surface of Mars, and sending spacecraft to visit every planet in the solar system, and I include Pluto in that because it was a planet at the time we launched that mission.

Of particular relevance to this hearing, we've been pioneers in the application of electric propulsion since the 1980s. In fact, right now there are some 160 spacecraft orbiting the Earth flying our electric propulsion products of one type or another.

As NASA looks to expand human presence in the solar system, development of efficient in-space transportation systems is critical. Solar electric propulsion, or SEP, is key to the sustainable architecture shown in the projected graphic by enabling efficient transfer of cargo, habitats and payloads to deep-space destinations in advance of astronaut arrival. Here's why that's important. Today we can land one metric ton on the surface of Mars. In order to do these human missions, we need to land 80 metric tons of supply and equipment. Mars missions will also send humans much farther than ever before. This combination of heavier payloads and the need to travel over greater distances drives us to seek a solution that takes advantage of strategic logistics planning.

An analogy to explain this approach is the way that military deployments are conducted today. First, the heavy equipment, supplies and other logistical items are pre-deployed by large cargo ships and planes to the region. Then once the equipment is in place, the troops follow by fast air transport. SEP systems are the equivalent to the cargo ship for deep-space missions. These systems are now under development by NASA and Aerojet Rocketdyne to reduce the amount of propellant needed for these space missions by a factor of 10. This is important because it costs just as much to launch propellant as it does to launch scientific instruments or other mission-critical equipment. With SEP, we can reduce the number of launches needed and thereby taxpayers cost to achieve the mission. We're well on our way to having efficient in-space transportation with SEP. We must continue to adequately fund these development and demonstration efforts.

The primary challenge facing high-power SEP development is the risk of losing focus as we go through the critical transition period from development to flight demonstration and subsequently operational use. This requires a stable budget and a constancy of purpose. Everything we do should be with the goal of landing human on Mars in the 2030s.

Currently, we're on a development path that will result in an SEP system capability in the 100-kilowatt to 200-kilowatt total power range. This is more than adequate for early outpost missions to Mars.

As SEP is scaled up to several hundred kilowatts, another challenge we face is managing the power transfer from the solar arrays to the thrusters. To reduce transit times, it's important that power is transferred as efficiently as possible. Since commercial spacecraft power systems are designed to power payloads and those are sized at 10 to 20 kilowatts, a power system from a traditional spacecraft cannot be adapted for a high-power SEP cargo vehicle. We're currently working on three separate SEP system developments with NASA, and details are provided in my written testimony.

So finally, let me just thank you, and I look forward to answering your questions about our in-space propulsion activities.

[The prepared statement of Mr. Cassady follows:]

Statement of

R. Joseph Cassady

Executive Director for Space Programs

Aerojet Rocketdyne

Before the House Committee on Science, Space & Technology

Subcommittee on Space

June 29, 2017

Good morning Chairman Babin, Ranking Member Bera, Members of the Committee and staff. I appreciate the opportunity to be here this morning to discuss how in-space propulsion will enable and enhance the Nation's space exploration efforts together with the Space Launch System (SLS) and Orion. Furthermore, I, along with the rest of Aerojet Rocketdyne employees across the country, appreciate the relentless work the Members and staff of this Committee have put forth to ensure that SLS, Orion, and the Nation's space program are a success. Your commitment to exploration and discovery should be lauded.

This is a time of great excitement and inspiration within the space community and for that matter across the country and around the world. We are putting the people in place and building the systems necessary to get humankind back to deep space and on to Mars and beyond starting in the early 2020s with the Deep Space Gateway.

Aerojet Rocketdyne Background

Aerojet Rocketdyne is a world leader in power and propulsion, supporting the Nation's defense, civil and commercial space efforts for over 70 years. Aerojet Rocketdyne has launched every astronaut from U.S. soil, and has been part of every U.S. mission to Mars. Among the highlights of our mission success heritage we have:

- powered every U.S. launch vehicle since the inception of the Nation's space program (Titan, Saturn, Space Shuttle, all Atlas, Delta IV and Delta II and the Space Launch System);
- flown on 135 Space Shuttle missions with 100% mission success;

- propelled spacecraft to every planet in our solar system; we're 7 for 7 landings on Mars, and we have even gone interstellar with Voyager;
- power and propulsion systems on NASA's Crew and Cargo service vehicles to the International Space Station;
- provided more than 90% of power systems to the International Space Station inlcuding the newly installed Li-Ion batteries;
- electric propulsion on more than 160 spacecraft of the approximately 250 electric propulsion spacecraft in orbit. (Figure 1)

Expanded Human Presence in Deep Space

As NASA looks to expand human presence in the solar system, starting with missions to lunar orbit and on to Mars, development of efficient in-space transportation systems is critical. Solar Electric Propulsion (SEP) is key to a sustainable architecture by enabling efficient transfer of cargo, habitats and payloads to deep space destinations in advance of astronaut arrival.

To provide a sense of scale, today we can land one metric ton on the surface of Mars; for a human mission we need to land 80 metric tons of supplies and equipment. Mars missions will also send humans much farther than ever before. This combination of heavier payloads combined with the need to travel over greater distances drives us to seek a solution that takes advantage of strategic logistics planning. An analogy which may help explain this approach is the way that military deployments are conducted today. First, the heavy equipment, supplies, and other logistical items are pre-deployed by large cargo ships and planes to the region. Then, once the equipment, barracks etc. are in place, the troops follow by faster air transport. SEP systems are the equivalent to the cargo ship for deep space missions.

SEP systems under development now by NASA and Aerojet Rocketdyne reduce the amount of propellant needed for deep space missions by a factor of 10. This is important because it costs as much to launch propellant as it does to launch scientific instruments or other mission critical equipment. SEP makes it possible to launch larger, heavier payloads thereby reducing the number of launches needed and the taxpayer cost for the total mission.

SEP Overview and Applications

Electric propulsion uses energy from sources other than chemical bonds to provide acceleration of propellant to obtain thrust. Because the energy is not limited to a chemical reaction, SEP can accelerate propellant to very high velocities, resulting in the use of less propellant to accomplish the same movement of the spacecraft.

A schematic of a typical SEP system is shown in Figure 2. The elements include the spacecraft's solar arrays which provide the power by converting energy from the Sun into electricity. This electrical power is then channeled into the propulsion devices through a series of electrical converters and regulators known collectively as the Power Management and Distribution system. For higher power systems, there are multiple thruster "strings." For example, in a 40 kW system there would be three active strings of 13 kW each. Each string consists of a thruster (Hall or ion), a Power Processing Unit (PPU), and a Propellant Distribution and Control System that regulates and supplies propellant to the thruster strings. There is also a digital interface to the spacecraft control computer that allow commands and telemetry to pass back and forth.

There are a number of applications for SEP including stationkeeping, repositioning, and orbit-raising for commercial, civil, national security and defense satellites. Additionally for deep space exploration, SEP enables bold missions such as visits to multiple asteroids accomplished by the DAWN mission. Building on the legacy of DAWN, SEP is an enabler for ambitious planetary missions such as sample returns in NASA's search for life on Mars and the Ocean Worlds. As mentioned previously, SEP will be used to preposition cargo in advance of human landings on other planetary surfaces.

SEP Development Challenges

We are well on our way to having efficient in-space transportation with SEP. We must continue to adequately fund these development efforts to ensure we will have the first human footprints on Mars in the 2030s. The primary challenge facing high power SEP development is the risk of losing focus as we go through the critical transition period from development to flight demonstration and subsequently, operational use. This requires a stable budget and a constancy of purpose. Everything we do should be with the goal of landing humans on Mars in the 2030s. As stated by the National Research Council in their Pathways to Exploration report, the pathway should be "characterized by logical feed-forward of capabilities." Currently we are on a development path that will result in a SEP system capability in the 100 kW – 200 kW total power range. This is more than adequate for early outpost missions to Mars, as depicted in the architectural approach shown in Figure 3.

As SEP is scaled up for NASA's deep space cargo missions, attention must be given to managing the power transfer from the solar arrays to the thrusters. Because electric propulsion is inherently low thrust, trip times are longer and can only be reduced by increasing the power to the thrusters. Therefore, it is important to ensure that power is transferred as efficiently as possible. Efficiency also plays a critical role in the heat rejection design of the spacecraft because power losses become heat that must be rejected, which drives the size and mass of the thermal radiators. This is especially important as power levels increase to several hundred kilowatts. A power system from a traditional spacecraft, typically sized at 10 – 20 kW, cannot be adapted for a high-power SEP cargo vehicle. Current commercial spacecraft power systems are designed to power payloads, whereas a SEP system directs the power to the electric propulsion thrusters.

Current SEP Development Programs at Aerojet Rocketdyne

Aerojet Rocketdyne is currently working on three separate SEP systems under contract to NASA. One is focused on deep space science missions; the second is focused on supporting human exploration of deep space; and the third addresses longer term technology development. The first two, NEXT-C and AEPS, have missions that are planned to launch within the next 2 – 5 years. In addition, Aerojet Rocketdyne is teamed with Sierra Nevada Corp. to develop a concept for a power and propulsion module that will include high power SEP for NASA's NextSTEP-2 habitation studies.

1) The NEXT-C xenon ion engine system is tailored to the needs of NASA's Science Mission Directorate. Under the program, a complete system is being developed that includes thrusters, power processors, and xenon flow controllers for delivery to NASA for use on science missions. One such mission is the Double Asteroid Redirect Target (DART) mission scheduled to launch in 2020. NEXT-C is moving forward toward the program Critical Design Review, which will be followed by build of the flight units for delivery to NASA.

2) Under the Advanced Electric Propulsion System (AEPS) program, Aerojet Rocketdyne is developing a flight version of the NASA HERMES 13 kW Hall thruster and a flight power processor, plus a xenon flow control system. This will result in the most powerful Hall thruster system ever flown when it is delivered in 2019. The program is fully funded and is working toward a Preliminary Design Review in August of 2017. Just this month, a series of tests was successfully completed at NASA Glenn Research Center that demonstrated stable operation of the system by the PPU over a range of conditions. This system will be demonstrated on a flight in 2021/2022 to prove readiness for use in a Mars cargo vehicle that would pre-position assets required by the astronauts during the first human mission to the red planet in the early 2030s. Originally, this demonstration was to be on the Asteroid Redirect Mission (ARM). In light of the recently announced cancellation of ARM, NASA has directed Aerojet Rocketdyne to continue working toward the 2019 delivery date so that the SEP demonstration can occur in 2021/2022.

3) The 100 kW Nested Hall Thruster is being developed as part of the NextSTEP program within NASA's Advanced Exploration Systems. A very high power thruster and a modular PPU are being developed, scalable from 50 kW to 200 kW. As part of the NextSTEP program, we will demonstrate the steady-state firing of the thruster and PPU at 100 kW for 100 hours continuously.

Aerojet Rocketdyne is committed to this nation's space exploration program from the ground up, and I look forward to answering your questions about our advanced in-space development activities.

Thank you.

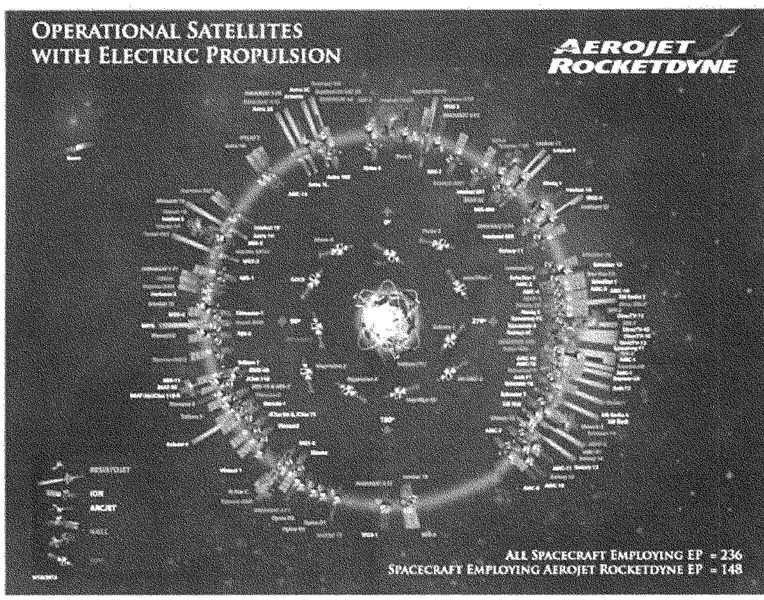


Figure 1 – Operational Satellites with Electric Propulsion

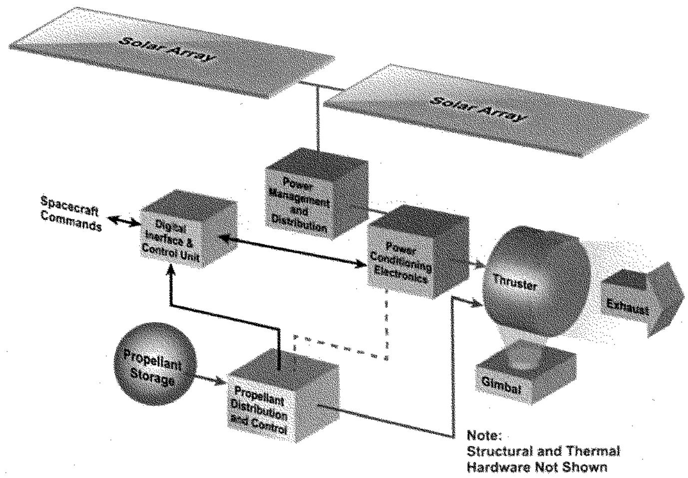


Figure 2 - Typical SEP System Schematic

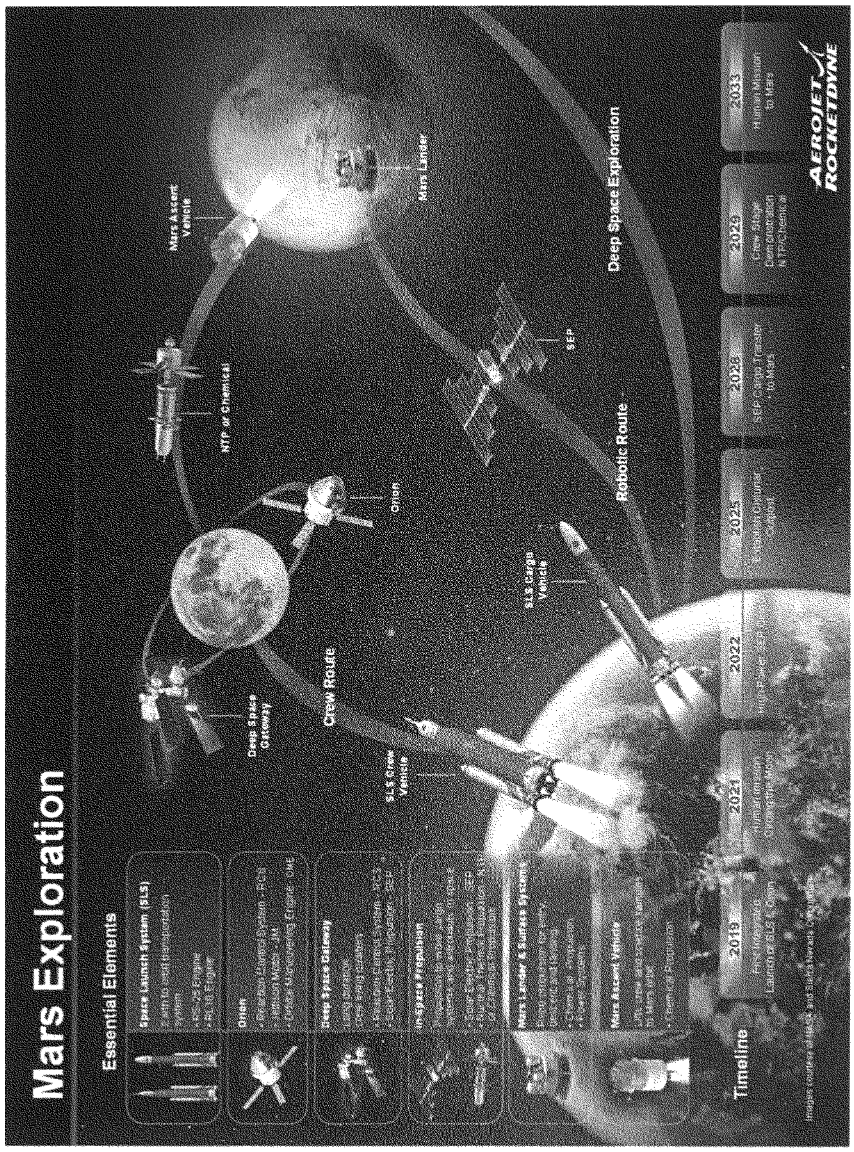


Figure 3. Aerojet Rocketdyne architecture concept for deep space exploration

Summary of Major Points

Solar electric propulsion (SEP) will play an important role in human missions to Mars by efficiently pre-deploying cargo and supplies.

SEP enables multiple planetary robotic missions, such as sample return from small bodies and Mars.

Electric propulsion is a mature technology used on more than 200 commercial and DoD satellites on orbit today.

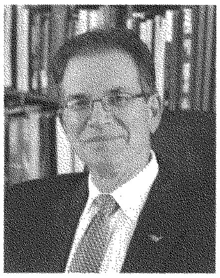
Technology development of high power (10 kW – 100 kW) electric propulsion is being funded now by NASA.

A mission demonstrating high power SEP capability is planned for the 2021/ 2022 time frame.

Challenges to development are more at a system level, especially efficient power transmission and regulation at 40 kW – 400 kW

Other challenges are more programmatic: maintaining focus and constancy of purpose.

Joe Cassady – Executive Director for Space Programs, Washington Operations, Aerojet Rocketdyne



Mr. Cassady is the Executive Director of Space Programs in the Washington DC Operations for Aerojet Rocketdyne where he helps oversee strategy development and architectures for future space and launch systems. He obtained his BS (1981) and MS (1983) in Aeronautics and Astronautics from Purdue University as well as a Graduate Certificate in Systems Engineering at the George Washington University in 2005. He has 33 years experience in propulsion and mission and systems analysis and has authored more than 50 technical papers dealing with electric propulsion, power and attitude control systems and mission analysis.

His experience includes flight projects for both the Air Force and NASA. Mr. Cassady led flight project teams for the 26 kWe ESEX arcjet system (which still holds the record as the highest power electric propulsion system flown) and the EO-1 Pulsed Plasma Thruster system. Both systems were accomplished within program cost and schedule constraints and were successful flight demonstrations. In addition, he has served on a number of advisory groups for NASA and the DoD. He is an Associate Fellow of the AIAA, is vice-president of the Electric Rocket Propulsion Society and serves as Executive Vice President and member of the Board of Directors for ExploreMars, a 501c(3) non-profit dedicated to STEM and human Mars exploration.

Chairman BABIN. Thank you, Mr. Cassady.
I'd like to recognize Dr. Pancotti for five minutes.

TESTIMONY OF DR. ANTHONY PANCOTTI, DIRECTOR OF PROPULSION RESEARCH, MSNW

Dr. PANCOTTI. Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, thank you for the opportunity to testify on in-space propulsion in the United States. I thank the Committee for its longstanding support of space exploration and plasma physics research in this country. I am pleased that the Committee is considering such important topics.

I would also like to thank the Air Force Research Laboratory including the Office of Scientific Research as well as the SBIR program, which initiated and developed FRC propulsion over the past decade.

High-power electric propulsion is a key technology for humanity's sustained presence in deep space. In order to build a permanent existence beyond the bounds of Earth, advanced in-space transport will need to break today's impulse and coast approach and advance to continuous direct burns to destinations in our solar system. For this approach to be effective, high specific impulse devices are needed. This metric ensures that a large fraction of the expensive masses we launch into orbit are payload and not just more propellant to get the job done.

Considering that even the most conservative manned missions to Mars are predicted to require almost 100 metric tons to reach the planet's surface, the cost of this endeavor becomes unsustainable.

The above argument for high specific impulse provides good testimony for all electric propulsion systems. While low-power systems could effectively transport spacecraft almost anywhere in our solar system, it would take years or even decades. A trip from Earth to Mars with today's electric propulsion and the world's largest solar array on board the International Space Station would take over ten years. These time scales do not lend themselves to a sustainable deep-space astronauts. To be truly a sustainable endeavor, high power is needed to deliver any significant amount of mass in a reasonable period of time.

While all the technologies being presented here today address this fundamental issue of high specific impulse and to a varying degree high power, MSNW's 100-kilowatt FRC thruster supported by the NASA program has some key advantages. In addition to the aforementioned, FRC propulsion is very light weight, and as we all know, lighter is faster, and for spacecraft, allow more payload on board. If humanity's intent is to explore, build and ultimately inhabit far-reaching destinations, it will require propulsion systems that are very light weigh.

Variable power is another area where FRC propulsion has strong advantages. Interplanetary missions that use solar energy have a large decrease in power as you travel further away from the sun. Because FRC thrusters are pulsed fixed energy devices, not fixed power devices, they can accommodate a large range of power inputs in a single design. This means that FRC thrusters can be validated in cislunar space and the exact same hardware can be applied to a Mars transfer mission.

Another important benefit with regards to power is FRC's ability to scale up. The physics of this technology were born out of the fusion community that currently operate FRC devices at energy levels that would correspond to a 70-megawatt thruster. Considering these origins, FRCs would be able to service the propulsion demands for several generations and expand deep space astronauts to Mars and the ocean worlds beyond.

The most unique characteristic of FRC propulsion is their ability to operate in a wide variety of propellants including oxygen, which typically degrades vital components in other propellant systems. FRC thrusters have been demonstrated on pure oxygen as well as carbon dioxide, a major component in Martian atmosphere. FRCs have also been formed on vaporized water, which is easily stored and available—maybe available throughout our solar system. As part of MSNW's NextSTEP program, the FRC thruster will be operated on Martian atmosphere and methane.

While this fact may have some benefit to traveling to Mars and beyond, the real advantages are when we return home, whether that trip is to bring back explorers or sample materials, the ability to refuel at almost any planetary body within the solar system has huge advantages. The cost savings of this approach are significant, and NASA is already focused on this topic called institute resource utilization.

We cannot have the future we want tomorrow without investing in its technology today. This is no easy task when there are many expensive and pressing matters that require our attention at home. While many of those matters cannot be ignored, we must keep our eyes lifted to the horizons and invest in our future. While this task may be daunting and overwhelming, it happens one step at a time.

By making strategic choices, the next step we take will put us on a path to the future that we all want. I applaud NASA and the U.S. government for their commitment to space technology and exploration, and with your continued support, my colleagues and I can make the right next step for a better future for all of humanity.

Thank you.

[The prepared statement of Dr. Pancotti follows:]

PREPARED STATEMENT OF

Dr. Anthony P. Pancotti
Director of Propulsion Research
MSNW, LLC

Testimony before the Space Subcommittee of the
House Committee on Science, Space, and Technology
United States House of Representatives

Hearing on In-Space Propulsion: Strategic Choices and Options
June 29, 2017

Chairman Babin, Ranking Member Bera, and Members of the Subcommittee, thank you for the opportunity to testify on in-space propulsion in the United States. I thank the Committee for its longstanding support of electric propulsion (EP) and plasma physics research in this country. In this hearing, I will brief the status of MSNW's high power electric propulsion system and provide testimony for our country's future investments in technology. While this technology may seem like a distant future, it is the strategic choices of the here and now that will set us on the path to make the unimaginable possible. I am pleased that the Committee is considering such important topics. The primary points of my testimony are as follows:

- High power electric propulsion is a key technology for humanity's sustained presence in space.
- Investing in technologies such as MSNW's Field Reversed Configuration (FRC) propulsion will allow NASA to build the foundation for long-term sustainable space exploration.
- Like most electric propulsion devices, FRC thrusters have the shared benefit of high specific impulse; this is a metric to measure the propellant efficiency of a propulsion device.
- FRCs have additional benefits of providing throttleable power and performance that allows for an even more efficient trajectory to be established.
- Mars cargo missions will be feasible with lower cost and higher fractions of payload delivered to the destination.
- FRC thrusters have a low specific mass compared to other EP technology, meaning this technology is not only high power, but also very lightweight.
- Born from fusion research, FRCs easily translate into megawatt power levels, opening up the exploration of distant ocean worlds.
- FRC propulsion devices are unique in that they can be fueled by almost any gas or vapor in the solar system, making it possible to refuel at distant locations.

INTRODUCTION

Science, space, and technology have been cornerstones of this country. The United States' prowess in these domains gives us a position of leadership on the world stage. Space holds a specific importance in the hearts and minds of many. This notion seems to transcend age, race, and culture and enthralls us all. The U.S. has been the leader in space technology since its beginnings. Not only is it a proud and identifying part of our culture, it produces countless beneficial impacts for America and humanity as a whole. The future of space exploration leads us past the mere orbit of Earth to explore and colonize our solar system. To do so we must make strategic choices today that will enable us to remain the leaders of tomorrow. One key technology required to build a sustained presence beyond Earth is high-powered in-space propulsion.

To build the foundation for sustainable exploration of our solar system, high specific impulse and high power in-space propulsion systems are required. The increased fuel efficiency associated with high specific impulse enables large payloads to be delivered at decreased costs. High power decreases transit times so that we can perform missions in days rather than years or decades. Both high payload mass fraction and fast trip time are required for a truly sustainable deep space architecture. NASA's NextSTEP program is supporting several projects to research and develop propulsion technologies that can accomplish both of these goals.

One such technology is MSNW's Field Reverse Configuration (FRC) thruster. FRC physics were originally investigated for fusion power applications dating back decades. The technology was first applied to in-space propulsion by MSNW through support from the Air Force Office of Scientific Research's Space Power and Propulsion group which proved that this approach to propulsion was feasible.[1] The technology has grown and developed over the past decade through several Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. The development of this thruster technology was supported by the Air Force Research Laboratory In-Space Propulsion Branch[2] and NASA's Jet Propulsion Laboratories which helped prove scaling to relevant energies and power levels.[3] The related electronics were fostered by the DARPA Tactical Technology Office which for the first time proved continuous operation of a pulsed electromagnetic power supply.[4] FRC thruster technology is currently part of the NASA's Advanced Exploration Systems' (AES) portfolio. In addition to the requirements of this program, FRC thrusters have several advantages including lightweight design, variable power, and the ability to run off almost any gas or vapor.

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[1] Slough, J., Kirtley, D., Weber, T. "The ELF Thruster-. International Electric Propulsion Conference" IEPC-2009-265 (2009).
[2] Brown, D., Kirtley, D., et al. "Development of High-Power Electic Propulsion Technology for Near-Term and Mid-Term Space Power". Joint Army Navy Airforce NASA Journal, 2010.
[3] Kirtley, D., Pancotti, A., Slough, J. and Pihl, C. "In-Situ Electromagnetic Propulsion for Martian and Terrestrial Atmospheres". AIAA Joint Propulsion Conference, 2012.
[4] Kirtley, D., Pihl, J., et al. "Development, Vibration, and Thermal Characterization of a Steady Operating Pulsed Power System for FRC Thrusters", Joint Army Navy NASA Air Force Conference, 2015.

ARGUMENTS FOR HIGH POWER ELECTRIC PROPULSION DEVELOPMENT

High power electric propulsion is a key technology for humanity's sustained presence in deep space. Future lightweight solar panels, and possibly nuclear fission, will enable high power propulsion systems to break today's "impulse and coast" approach and advance to continuous direct burns to destinations within our solar system. These power levels enable humans and large-scale cargo missions to the Moon and Mars with a significant reduction in cost and trip time compared to existing EP technologies. These saving are even more dramatic when compared to chemical propulsion alternatives.[5]

When comparing propulsion systems for cis-lunar missions, chemical propulsion systems can deliver small cargo relatively quickly (few days), while high-power EP systems can deliver much larger cargo, albeit at a slower pace (hundreds of days). For example, it was shown[6] that a 1-2 MW EP thruster operating at 3000-5000 seconds of specific impulse allows for a two-fold increase in available transport payload between low-Earth orbit (LEO) and a low-lunar orbit (LLO) when compared to a chemical bipropellant system (32-40 mT versus 18 mT, respectively). The impetus for a high-power EP Earth-Moon cargo tug is strong due to the scope of the proposed scientific and manned missions in cis-lunar space. Furthermore, the entire system could be reused, allowing dramatic mass and cost savings.

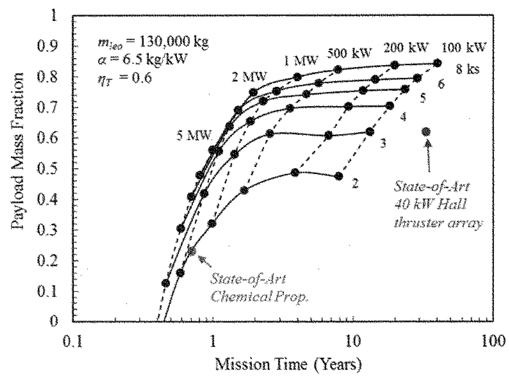

Figure 1: Mission envelope for an Earth-Mars cargo transfer using the FRC propulsion. EP mission model uses a minimum-time transfer between Earth escape and Mars orbit. A Hohmann transfer is used to model the chemical propulsion mission.

High power EP is especially beneficial for solar system exploration missions. Consider, as an example, a cargo transfer between LEO and Mars orbit. The study in Figure 1 calculates the payload mass fraction for a desired mission duration considering a specific impulse range of 2000-8000 s and a power range of 100 kW to 5 MW. As a point of reference, Figure 1 also includes the results for a state-of-the-art chemical bipropellant system (450 s specific impulse) and Hall thruster array (40 kW at 3000 s specific impulse and 60% efficiency[7]).

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[5] Grossman, L. "Ion engine could one day power 39-day trips to Mars", New Scientist, 22 July 2009.
[6] Glover, T., Chang Diaz, F.R, et al. "Projected Lunar Cargo Capabilities of High-VASIMR Propulsion". IEPC-2007-244, 2007.
[7] Brophy, John, et al. "Asteroid retrieval feasibility study." Keck Institute for Space Studies, Califonia Institute of Technology, Jet Propulsion Laboratory (2012).

Of primary importance is the drastic increase in payload mass enabled by high-power EP technology over chemical systems. This increase can amount to nearly three times the delivered payload at high specific impulses. There is also a clear trend showing the benefits of higher power concerning trip time. Notice in Figure 1 the shift towards significantly lower mission times at higher powers. In the extreme case, a 1 MW thruster operating at 8000 s specific impulse could deliver nearly 85,000 kg to Mars orbit in less than three years. While mission duration with high power EP are longer than the equivalent mission using a chemical propulsion system, this can be overcome with more power. A 5 MW system at 5000 seconds specific impulse could make the trip as fast as chemical, but with over twice the payload.

ADVANTAGES OF THE MSNW'S FRC THRUSTER PROGRAM

The technologies currently funded under the NextSTEP program address the fundamental issue of high specific impulse and in varying degrees, high power. Each has its own approach and corresponding advantages and disadvantages. The MSNW's FRC propulsion system is in the early stages of development compared to the other technologies in the NextSTEP portfolio, however it has several distinct advantages.

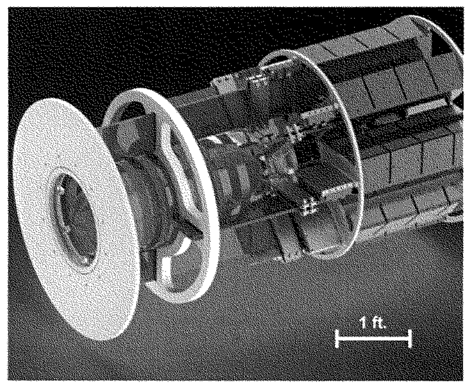

Figure 2 CAD Model of the MSNW's NextSTEP Thruster. Hardware shown is for the experimental hardware to be evaluated in a laboratory environment and are not indicative of flight hardware. Estimated performance is 2000 to 5000 s of specific impulse with Argon and Xenon propellants. System efficiency predicted to be 32 to 75%

In addition to the aforementioned attributes of high specific impulse and high power, FRC propulsion devices have low specific mass. Specific mass is another metric spacecraft designers use similar to specific impulse. Instead of reflecting the mass of propellant like specific impulse, specific mass represents the mass of the thruster itself. It is easy to understand why this metric is important. As with any form of transportation, the lighter the means of transport, the more cargo can be delivered. If humanity intends to explore, build, and ultimately inhabit far off destinations, it will require a transportation system that is lightweight and can effectively deliver goods and materials throughout the solar system.

While there may be debate about the ideal power level, there is a general consensus in the space community that hundreds of kW in the form of Solar Electric Power (SEP) is the best current application, with the ultimate goal of reaching megawatts in the future. FRC propulsion is a strong application for both. An interplanetary mission that uses SEP will have a large variation in power throughout its route. As the spacecraft gets farther from the sun, less power is available. In fact, a 100 kW solar panel at Earth would only produce 42 kW of power at Mars. Because FRC thrusters are pulsed, fixed energy devices, not fixed power devices, they can accommodate a range of power inputs within a single design. For example, the NASA NextSTEP program, the FRC thruster will create 100 J plasma discharges. By repeatedly creating these discharges every millisecond, the thruster operates at 100 kW. By simply slowing down the period to 2.4 milliseconds the thruster can meet the 42 kW constraint enabling one thruster, optimized for a particular energy level, to operate over multiple power inputs. This variability means FRC can be tested and validated with the next generation of power for cis-lunar SEP missions and the exact same hardware and thruster could be applied to Mars transfer missions.

The need for more power is clear and will be required for long-term habitation of the solar system. While FRC propulsion will be demonstrated with hundreds of kW during the NextSTEP program, the physics and technology behind it was originally researched at much higher power levels for fusion applications. Born out of the fusion community, FRCs have always inherently been high power (energy) devices, which the spacecraft propulsion community has previously reduced in size and power to be more applicable to current space applications. The highest energy, currently operational FRC device is at Helion Energy in Redmond, WA and forms 35 kJ FRCs in a deuterium plasma and then compresses them to MJ energies for fusion applications. A one megawatt FRC thruster would only require formation energy of approximately 500 J at 500 Hz. Because FRCs have such a high energy density, scaling laws predict a 500 mm exit diameter at 1 MW. The physical size of such a device is quite practical for fabrication, testing, and fitting within a payload faring. For such a thruster, there would be no need to create large arrays of the thruster in order to achieve higher power. In this manner, FRCs can service the propulsive demands for this generation as well as those that follow. When megawatt-class power is available in space, FRC propulsion will be ready to extend deep space architecture to Mars and the ocean worlds beyond.

The final and most unique characteristic of FRC propulsion is its ability to use a wide variety of propellants. The FRC thruster being developed at MSNW is inductively coupled to the propellant, meaning there is no physical contact with hot plasma. All the process from formation to acceleration are done through interaction of magnetic fields. Consequently, there are no electrodes or nozzles to erode or degrade over time. Moreover, since there is little or no physical interaction with the propellant, almost any propellant can be used. Typically, oxygen, or a

MSR Propulsion Choice	Bipropellant	ELF	ELF with ISRU
Delta V Required: LEO-MOI-LEO	6.5 km/s	8 km/s	8 km/s
Specific impulse	450 s (out)	3000 s (Xe)	3000 s Xe/Ar
Propellant Mass to Mars [kg]	17,561	5,338	5,338
Propellant Mass from Mars [kg]	5,007	4,114	5,338
Solar Panel and Thruster Mass [kg]	0	1,300	1,300
Return payload [kg]	**408**	**12,248**	**16,362**
Payload fraction	<2%	53%	71%

Figure 3. Simplified model of a Mars Sample Return Mission. Model uses a Delta 4 Heavy vehicle (23000 kg to LEO), assumes optimal mars orbit, spiral EP trajectories, propulsive breaking maneuvers, and 5 kg/kW solar panel mass. ELF is 1.5 kg/kW with 200 kW of onboard solar power. Identical payload is assumed to travel and return.

molecular propellant containing oxygen, corrode vital components in electric propulsion system. However, FRC formation has been demonstrated in pure oxygen as well as pure CO_2 and simulated Martian atmosphere. FRCs have also been formed from vaporized water, which is another resource that is easily stored and may be available throughout the solar system[8].

While this ability to operate on various propellants may have some benefits when traveling to Mars and beyond (in terms of depots and waystations), the real advantage is the return mission. Whether the return trip is to bring back explorers or sample materials, or perhaps just to return the spacecraft so it can be used again, the ability to refuel at almost any planetary body with water or an atmosphere is a significant advantage. The cost savings of such mission architectures are large, and is already the subject of NASA's in-situ research utilization (ISRU) initiative.

To illustrate the immense advantages of IRSU, an example 200 kW Martian Cargo and Sample Return Mission was studied at MSNW (see Figure 3). As expected, it showed that the higher specific impulse of an electric propulsion system would yield dramatic mass savings. Even with the additional mass of a large solar panel system, the payload capability of a high power EP mission is much greater than what is attainable with chemical propulsion. Furthermore, an FRC thruster utilizing ISRU Argon from the Martian atmosphere yields can increase the payload returned to Earth by over 4000% over a chemical system.

Conclusions

We cannot have the future we want tomorrow without investing in its technology today. This is no easy task when there are many expensive and pressing matters that require our attention at home. While too many of those matters cannot be ignored, we must keep our eyes lifted to the horizon and invest in our future. While this task may seem daunting and overwhelming, it happens one step at a time. By making the right strategic choices, the next step we take will put us on a path to the future we want. I applaud NASA and the U.S. government's commitment to space technology and with your continued support, my colleagues and I can make the right next step forward for a better future for all humanity.

The following list is recommendations to further science, space, and technology in this country with regards to in-space propulsion:

1) Continue to fund the development of high power electric propulsion and a follow-on to the NASA NextSTEP program that transitions all of these technologies to flight.
2) Accelerate advances in space power systems that can enable fast transit time while at the same time reduce system mass, cost, and risk.
3) Increase NASA centers capabilities for testing high power EP systems. The demanding test conditions of these new technologies require enhancements for NASA's world-leading facilities.

[8] A. Pancotti, J. M. Little, et al., "Electrodeless Lorentz Force (ELF) Thruster for ISRU and Sample Return Missions." 34th International Electric Propulsion Conference, Kobe, Japan, IEPC 2015-67. 2015.

BIOGRAPHY FOR ANTHONY PANCOTTI

Dr. Anthony Pancotti is the Director of Propulsion Research at MSNW, LLC in Redmond, WA. He earned his Ph.D. in Aerospace Engineering in 2009 from The University of Southern California, were he designed, built, and tested an experimental high-efficiency electro-thermal ablative pulsed plasma thruster, called a capillary discharge.

Subsequently, he was hired by the Air Force Research Laboratory at Edwards AFB to continue his research and development of this concept. It was during this research that he demonstrated unprecedented specific impulse and efficiencies for this class of devices. As part the Advanced Concepts Group at the AFRL, Dr. Pancotti reviewed and investigated a range of advanced propulsion concepts, including FRC propulsion.

In 2011, he joined a team of researchers at MSNW to work on a variety of fusion, propulsion, and plasma concepts. Presently, Dr. Pancotti is the Principle Investigator for MSNW NextSTEP propulsion program. As the Director of this research group, he is a co-investigator on several additional research projects including lower power FRC research for the Air Force and plasma Magnetoshell aero braking for NASA. Currently he holds a portfolio of five advanced propulsion and applied plasma research topics and leads of team of five researchers and technical staff.

Dr. Pancotti is the author or co-author of over 40 refereed research publications on diagnostics, plasmas physics, and space propulsion. He is an active member of his research community, having peer-reviewed papers for the *Journal of Spacecraft and Rockets* and the *Review of Scientific Instruments*. He has served as chair, co-chair, and session organizer for the Joint Propulsion Conference (JPC), The International Electric Propulsion Conference (IEPC), The Joint Army Navy NASA Air Force (JANNAF) Conference, and Advanced Space Propulsion Workshop (ASPW).

Chairman BABIN. Thank you, Dr. Pancotti. Fascinating testimony. I notice we had even some more young folks come into the room. It's great to see so many people here this morning to hear this testimony.

I'd also like to introduce two interns I've got that are sitting over there, both of them real small fellows. You all stand for us, Bo Swanson and Jonathan Ladd. We need a bigger office, I can tell you that.

Anyway, we appreciate all of you being here this morning, and thank you for this testimony.

I want to thank the witnesses for your testimony, and I'd like to recognize myself for five minutes of questions.

I'd like to direct this to Dr. Chang-Diaz and Mr. Cassady and Dr. Pancotti because I'd like for you to kind of delve into it a little bit more for the benefit of all of us here. What capabilities—and let me just say this—I've had the privilege of touring and visiting two of you guys' facilities, very, very interesting. What capabilities does your specific technology have that makes it unique? We'll start with you, Dr. Chang-Diaz.

Dr. CHANG-DIAZ. For the VASIMR, there are certain features that are unique. One is that it can vary the thrust and the specific impulse of the rocket, keeping the power the same. It's essentially the same thing that you do when you shift gears in the car, and if you drive a car like a racecar driver you step on the gas and you never let go and all you do is shift gears, and so when you're climbing a steep hill, you would want more torque in your wheels so you shift to higher thrust, and when you are speeding in flat terrain such as interplanetary space, you would want to upshift to fifth and sixth gear, and then you will have a higher specific impulse, still the same power, maximum, because you paid dearly for the power. And so it's important to have that feature. That's one.

The other one of course is that when you're dealing with plasma, you're talking about very hot substances, and you want to keep them off of the surrounding rocket casing, so you want to have magnetic nozzles, magnetic pipes that guide the plasma. The way you heat the plasma also is unique. We use electromagnetic waves, pretty much the same way you heat your coffee in a microwave oven: you don't touch it. You just launch these waves and these waves wiggle the plasma and get it really hot, and we're talking about temperatures of the order of two to three million degrees. So these are some of the features, and that gives you a great deal of capability to open up in the technology, so that's a summary.

Chairman BABIN. Mr. Cassady?

Mr. CASSADY. I think the unique feature of our approach on the NextSTEP program is that we're building upon what we've already flown. Our device that runs at 100 kilowatts is what we call a nested Hall thruster, and there's some description of it in the written testimony, but just for the group here today, we fly a 5-kilowatt Hall thruster on the advanced DHF spacecraft now as was mentioned earlier. It has a single annular region where the plasma is generated. The nested Hall thruster takes that, adds a second ring outside and then even a third ring, and each of those rings you're running essentially the Hall discharge. So we're able to take what we've known today that we fly today and scale it up simply without making it that much physically larger, we can scale it up to the much higher power.

The other part of it is, I'd really like to delve into the system aspects. Because we're doing that approach, we're able to also deal with the power processing issues that we've learned a lot of lessons on in our flight experience—I'm not sure what's going on there.

Chairman BABIN. Ignore that.

Mr. CASSADY. Ignore it? Okay. Thank you.

So the other half of the system—the thrusters are obviously very important part and they're the visible part that we all see but the other half of the system is the power, and Franklin referred to that. We have to shepherd that power through very carefully because wasted power is time to us. We need all the power we can get to keep that time down. So we're building blocks that we've learned from our flight experience into modular designs that we can scale up incrementally to these higher powers, and as Steve Jurczyk mentioned earlier that we are also working now on the 12–1/2-kilowatt Hall thruster. It's another incremental step. So incrementalism is my, I guess, word that I would use.

Chairman BABIN. Thank you very much.

Dr. Pancotti?

Dr. PANCOTTI. Thank you, Mr. Chairman. I think in my testimony I highlighted quite a bit about what we call ISRU, in-stage research utilization, and for me, when we're looking long term towards sustainable infrastructures in space, to become a spacefaring race or a multi-world species, advanced capabilities that will allow us to use the resources of our solar system will become vital. Just like today, if you wanted to drive across our country, you wouldn't fill up an 18-wheeler worth of gasoline to make it. You would stop along the way and refuel, and I feel this is a very important aspect of building a sustainable infrastructure to be able to go to Mars, scoop up atmosphere, and use that to propel your spacecraft to the next destination or to return home. ISRU has a large payoff for return missions and also return missions from icy moons. So if we did want to go to far-off destinations, asteroids or icy moon planets, we could take water, use that as propellant and return very large samples to Earth.

The other aspect I think that is fairly unique about FRC propulsion is the power. Not only is it scalable for a very, very large range of powers, like I indicated for many generations of propulsion systems to come, we can use the same technology but also the ability to vary that power over a mission. Because it's fixed energy, we can optimize an impulse for an exact energy condition, and then by changing how often we fire it, we optimize it or we can use it over a very, very large of power within a single design.

Chairman BABIN. Thank you very, very much.

Now I'd like to recognize the Ranking Member of our Subcommittee, Mr. Bera.

Mr. BERA. Thank you, Chairman Babin.

I'm a simple person. I'm a doctor, not a rocket scientist, but if I'm thinking about this correctly, let's think about it in the context of travel to Mars just for sake of being concrete. We know the distance that we have to travel. We know the safe amount of cosmic radiation that a human being can get exposed to in terms of the time potentially. I think just listening to the testimony, we can think about this in two different ways. If we're sending supplies that are nonorganic, non-human beings, you know, you can send that at one speed, perhaps using one type of propulsion system, but then if we are sending human beings, we've got to send them at a different speed, perhaps faster, but at less weight. Am I thinking about this correctly? You know, just as a doctor, you could also then think about as we're thinking about how to send them faster, you know, what kind of additional shielding potentially we could do to prolong the time that they could be exposed to cosmic radiation. That's correct as well?

So it's not an either/or, it's, you know, perhaps all of these propulsion technologies that we ought to be thinking about here as well as, you know, working with our scientists and the folks that are looking at that.

Dr. Pancotti, you also talked about taking water, if we find planets with ice and, you know, there's some thought that, you know, part of our travel back to the Moon is potentially looking for ice in some of these deep craters that could—that we could then turn into fuel and use the Moon as a launch site. Is that correct or——

Dr. PANCOTTI. Yeah, that's correct. Earth has a very deep gravity well, which means it's very expensive. That's why it costs so much to launch mass out of our gravity well. If we can find resources outside our gravity well or in smaller gravity wells that we can use, it will ultimately save us money.

Mr. BERA. Okay. So for us as we're thinking about it and explaining to our constituents and the public, when they say well, we've already been to the Moon, why would we want to go back to the Moon. One reason we would want to go back to the Moon is that that is a potential secondary launch site. Is that—or not?

Dr. PANCOTTI. Yes.

Mr. GERSTENMAIER. Yes.

Mr. BERA. Well, again, I'm using your expertise to make sure I'm educated so that when I'm out talking to constituents and they ask these questions or talking to the broader public, it's like well, here's why this matters, or if they say well, why are you looking at solar propulsion or different technologies, well, here's why this matters.

So, you know, kind of looking at the human element, maybe, you know, Mr. Gerstenmaier, what is that—you know, just to kind of put it in context, what is that safe time for a human to be exposed, you know, using current technology, again thinking about travel to Mars?

Mr. GERSTENMAIER. When we look at Mars today, basically with chemical propulsion, the transit time to Mars is roughly about a year or so and a year return. That's right at the limit of the radiation levels that a human can tolerate. So we might have to take a small waiver to some of our radiation constraints but we can basically make it with chemical propulsion. The big advantage here with the higher-power electric propulsion is you can cut that time down and get more margin and so the radiation exposure for our crews is dramatically less. So I think that's interesting about this technology is, it really opens up our way to do mission design, the way you described. We've talked about the gravity well being tough to leave the Earth. it's much nicer from the vicinity of the Moon or a high elliptical orbit around the Moon. Now we can station keep there with electric propulsion, then use these high-energy power systems to transit the Earth-Moon system to these distant locations with much higher speed with a higher thrust level. So this technology really opens up the ability—we can do mission design to essentially optimize the overall systems design since we've minimized the exposure of the human to radiation in a microgravity environment.

Mr. BERA. So we really should be thinking about multiple modes of propulsion.

You know, one theory that someone was also suggesting were these Lagrangian points where, you know, things can sit stationary potentially for lack of a better way of describing it, having a gas station up there where, you know, having propellant up there, you break through the gravity well, you're able to able to go up there, refuel, and then go on. Is that just theoretical or is that something that folks think about?

Mr. CASSADY. I think as Bill was just saying, some of the groups getting together now to study how we go, what this architecture ought to look like, and you saw a little bit of that in the graphic I put up, one of the thoughts is, you could aggregate things out there in the lunar vicinity and then depart from there, and part of that aggregation—when I say aggregate, I mean bring different pieces of the eventual Mars spaceship to that point and that could include fuel. So—and then as Anthony alluded to in his testimony, you know, as we get better at making fuel on other places where we're going, we don't have to, you know, use the gas station or bring everything from Earth. We'd like to use the things that we find when we get out there into the solar system and perhaps we have a couple more nodes in the overall subway system, if you want to consider it like that, going between Earth and Mars where we can refuel the systems.

Mr. BERA. Great. Thank you. I'll yield back.

Chairman BABIN. Yes, sir. Thank you.

I'd like to recognize the gentleman from Oklahoma, Mr. Lucas.

Mr. LUCAS. Thank you, Mr. Chairman.

Mr. Gerstenmaier, what we seem to be talking about here, I think can best be described as the concept of extensibility, that technologies developed in the near future will be useful for future exploration as well, and extensibility prevents the development of incapacities. Discuss with us for a moment how NASA ensures that its investments in in-space propulsion technologies have that ability.

Mr. GERSTENMAIER. Again, I think as you've kind of heard from this discussion, we're kind of investing in a variety of technologies so we don't pick one technology to focus on solely. We do the broad agency announcements to go look at a variety of technologies. We test those on the ground. We make sure they show promise. We have this requirement for this 100-kilowatt system to run for 100 hours. That's a good proof of concept that can be done on the ground. Then when that's kind of behind us, we know the system is mature enough, then it can start being fielded into an operational system, and for example, the concept of the habitat around the Moon that uses a 12–1/2-kilowatt system that Steve and the Space Technology Mission Directorates have been investing in, that's a step up from where we are with electric propulsion today and Hall thruster regime but that's an incremental step moving forward. So I think by taking these steps but also investing in these far-reaching technologies that are not yet—we're not sure what promise they have, that's also advantageous too so we need to have that mixed investment philosophy of where we're looking at each one of these but then we also look at the application moving forward.

So we know today commercial communication satellites have electric propulsion on them. If we go to this 12–1/2-kilowatt size, that can remove the liquid apogee motors that are used from some launch vehicles that even helps the commercial satellite industry more. So these things have application not only for NASA use but also for use of the next generation of satellite technology. So I think we invest in a variety of activities not knowing exactly where the outcome is and we do it in a measured way that we can then get the best technology for future applications.

Mr. LUCAS. Along that very point, Dr. Chang-Diaz, Mr. Cassady, Dr. Pancotti, would you expand for a moment? Besides the government interest, and we just talked about this to a degree, how would you quantify commercial interest in high-powered in-space propulsion systems, gentlemen?

Dr. CHANG-DIAZ. For our company, we started out actually as a purely private venture, and it was all funded by private investors, and our interest was not really to go to Mars because going to Mars is really not a good business right now. So—but it is important to build the scaffolding that eventually will make it into a good business, and right now the business of space is closer to Earth, and so our vision is more of the vision of the trucking business of space, you know, building essentially a logistics capability, an electric high-power electric truck, and we think of ourselves as sort of the diesel engine of space that enables all these trucks to be traveling back and forth between the vicinity of the Earth and the Moon to make some revenue for the company and then as needs expand why we go further, so that's the vision.

Mr. LUCAS. Mr. Cassady?

Mr. CASSADY. I would just say very similarly, we've been in the commercial side. We're supplying hardware now to most of the commercial satellite providers who fly electric propulsion. What we do see, as Bill said, as we're working with NASA on these higher-power devices, there are other functions on those spacecraft that can be accomplished like taking them from the drop-off orbit where the launcher leaves them to their final destination. Then there's a whole world of expanding possibilities that we're seeing open up. People are talking about these large 6,000 satellite low-Earth orbit constellations. Those satellites have to go to individual points around the globe and be positioned. You can do that very effectively with a space tug, and I like Franklin's term, the space truck. We think of it very similarly. It's pretty, you know, multipurpose. It really serves a lot of different functions. We see interest in the DOD world because they're looking at reducing the cost to get their assets where they need to be, and as well as improving the resiliency of the assets, and that all involves more maneuverability in space, which is, again, something that solar electric can provide to them.

And then finally, I would say, you know, there's going to be probably an expanding sphere of influence of the economy as we move out and do these exploration missions around the Moon. We're going to start supporting people who want to go mine the Moon and do things like that. They're going to need transportation systems as well, and so as we're moving out to Mars, they're going to be coming along behind us and doing things that are economically viable and they'll need these transportation systems to support that.

Mr. LUCAS. Thank you.

Mr. Chairman, I see my time's expired.

Chairman BABIN. Yes, sir.

Now the gentleman from Virginia, Mr. Beyer.

Mr. BEYER. Thank you, Mr. Chairman, very much, and thank you for holding this hearing. It was just fascinating.

Dr. Chang-Diaz, you've been in space, and I was impressed with your opening paragraph where you said "In securing our ability to travel in deep space safely and sustainably, we're also ensuring the survival of our species." Can you expand on that? Are you worried about the survival of our species, and how will going into deep space help that?

Dr. CHANG-DIAZ. Well, this has been voiced by many of my colleague astronauts, and we all believe that, you know, we are all astronauts in this one planet that we have, and it's the only one we have, and we have no redundancy, and astronauts like redundancy. You know that. You know that. And so if you look at the way humanity is all housed in this, you know, this one ball, it is our life support that matters right now. We have no way to survive if something were to happen to us, something that could be brought by some external beyond our control event, we would be history that no one could tell, and it doesn't matter that much to the universe whether we are here or not but it does matter to us. And so I think the important thing here is for us to enable ourselves to be beyond and to work beyond and live beyond our Earth is fundamental to our survival.

Mr. BEYER. Thank you very much.

Dr. Pancotti, much of this testimony in this hearing is with the understanding that the Asteroid Redirect Mission was canceled and that all the work that was done basically—I mean, some of it moves forward. I want to ask this of our NASA gentlemen but was it a mistake to cancel it and to defund it?

Dr. PANCOTTI. From my personal view, I don't think it is. I like to use the term, keep our eye on the prize, and that prize is Mars. I think the next step forward for humanity I think is a huge calling like Dr. Chang-Diaz mentioned, to get to Mars and put people on another planet, and in doing so, I think the most direct approach to that is the best path forward.

As far as technology goes, propulsion devices, all three of us that are here talking today, those propulsion devices were initiated under the ARM mission and they are one of the most direct technologies that is going to move forward. No matter what we do in deep space, we are going to need advanced propulsion.

Mr. BEYER. Great. Thank you very much.

Dr. Walker, in your both written and oral testimony, you wrote—you said "Investments are required in electric propulsion technology across the spectrum of expected time to return on investment." Is that just a really polite way of saying that they show no return on investment?

Dr. WALKER. No, it's not.

Mr. BEYER. Or not in our lifetimes. And is it reasonable to expect a reasonable return on investment when we're talking about the exploration of deep space?

Dr. WALKER. Sure. Let me explain. I think the spectrum is very important. There are commercial things right now that impact our economy from how we deliver commercial satellites. That's a significant business. That business is up for grabs now as electric propulsion has become more mainstream, and the country or group that creates the next best electric propulsion device will own that business. So we need to make some very short-term investments so that we can make sure we have that. In the long term as the power available on orbit continues to rise, then we can begin to feed in these higher-power devices. So yes, it's a spectrum, some things that will be very impactful in the next five years and other things won't see for 15 to 20 years. Does that answer your question?

Mr. BEYER. Yes, it does. Thank you very much.

Mr. Cassady, you talked about how you're on the development path that results in SEP system capability in the 100-kilowatt to 200-kilowatt power range, and yet we heard I guess Dr. Chang-Diaz's company, they're already doing a consistent 200 kilowatt. Are you lagging behind or is it just because there's different technologies with different uses, or—you know, you seem uncompetitive relatively.

Mr. CASSADY. So I guess what I was trying to focus on there was the total system power that we need to get to Mars in the 2030s, and my point was, we don't need to go to a megawatt to be ready to go to Mars; we can do it with 100 to 200 kilowatts. We've done a lot of internal studies on the architecture as was shown in the diagram that I presented there, and I know our colleagues at NASA are doing the same thing. What we're trying to do, and I used the word "incrementalism" earlier—we're trying to come up with a "walk before you run approach," approach, I guess. We know the budgets are tight. We know that we're going to have to work under a constrained budget environment for the foreseeable future, and within that environment, we're trying to be responsible and say what's the minimum amount that we need to have to ensure we can do this mission and make the mission close, and for the cargo part of that mission, we can live with about 200 kilowatts, something in that range.

Mr. BEYER. Great.

Mr. CASSADY. That's for the total system, and then the idea is that we plug in these 12–1/2-kilowatt thrusters that we're developing right now for STMD onto that vehicle and that would be the cargo vehicle. That's why most of that payload that we talked about to Mars before the astronauts get there and pre-deploy it.

Mr. BEYER. Great. Thank you.

Mr. Chair, I yield back.

Chairman BABIN. Yes, sir. Thank you.

Now the gentleman from California, Mr. Rohrabacher.

Mr. ROHRABACHER. Thank you very much, Mr. Chairman, and thank you, Mr. Chairman, for having this hearing today and organized as it is so that we can have a better understanding of the goals and the technology needed to achieve those goals, and I appreciate the witnesses and I appreciate your leadership on this.

We had a hearing on materials and the development of new materials and how that relates to human progress yesterday or the day before, and when we are talking about the electric propulsion systems now which is being presented to us as some new type of options that we have, how much of this is dependent, was dependent on new materials? Is this something that's part of this formula? Whoever wants to, go right ahead.

Dr. CHANG-DIAZ. It was quite dependent on materials, advanced materials, particularly when you deal with very hot plasmas, and you have to encase these plasmas in materials that will not erode away or melt away, so there are some special ceramics that have been developed that enable us to shine these electromagnetic waves and make the plasma hot yet they go right through the walls of the rocket. So the material development has been critical.

For us, some of the means of delivering this energy to the plasma requires materials and special antennas and special coatings that we use, very new materials, of course, that are proprietary right now but definitely materials is very important.

Mr. ROHRABACHER. Do any of these materials—I have not been a friend of necessarily spending more money on fusion energy. I felt that was something that doesn't seem like we've made much progress. However, I've been told that fusion energy, or actual or attempt to develop it has helped produce new materials. Is this part of that?

Dr. CHANG-DIAZ. In our case, it is, and I think in the case of Anthony's as well. I think we both have the same pedigree from the fusion energy program way back in the—well, he's a lot younger but I go back to the 1970s when we were trying to develop fusion and they told us it was 20 years away.

Mr. ROHRABACHER. In light of that expression where the young kid says "I don't know where I'm going but I'm on my way," and I think with fusion energy, as I say, I've been skeptical. I'm working to the point where we can use it for the production of electricity here but we can see that there's benefits that we don't know were going to happen, and so I'm very pleased to hear that all that money that we spent on fusion energy didn't go to waste. So thank you very much.

I'd like to ask Mr. Jurczyk about the choices here that we do have, and maybe it's like a choice between fission and fusion. I don't know. But the idea of having a refueling station, cryogenic propellant storage station there, is that with this type of new technology that we're taking about developing and putting into place, is it still important for us to do cryogenic storage facilities and refueling, basically refueling stations if we have this capability?

Mr. JURCZYK. As Mr. Gerstenmaier mentioned, one of the real advantages of electric propulsion is the storability of the propellant. So for the 12–1/2-kilowatt thruster system, xenon is the propellant and xenon is storable, and so we don't have to come up with credibility to either passively or actively cool the system to keep that propellant available to the thruster system. However, if we look at more advanced chemical propulsion systems like locks hydrogen propulsion systems for space, and that would require advances in technology for both long-term storage of locks and particular hydrogen, long-term storage of hydrogen is very challenging and you'll need active cooling to be able to do that in transfer technologies. So that would be more geared towards if we went to higher-performing in-space chemical propulsion stages. The real advantage of electric propulsion is the storability of the propellant and not needing to go to cryogenic propellants.

Mr. ROHRABACHER. I'm not sure if that was a yes or no, but—do we see that if we're going to be having a successful—there's talk that maybe—you know, keep your eyes on the prize, like you say. I'm not necessarily involved with trying to eliminate all these other options we need to do in space in order to just get to Mars, but in order to do some of our Moon—if we readjust so it's Moon first, then Mars, will we need a cryogenic storage facility as compared to a deep space propellant like was being described today?

Mr. JURCZYK. Yeah. If we continue to go down the route of chemical propulsion, we talk about—we talked about being able to produce a fuel with water resources on the Moon and then being able to handle that propellant, store it and transfer it would be a capability we'd want to need if we wanted to use that ISRU capability on the Moon as was mentioned previously, yes.

Mr. ROHRABACHER. Well, thank you, gentlemen, very much. It's been a very educational experience. God bless.

Chairman BABIN. Thank you.

Now I'd like to recognize the gentleman from Florida, Mr. Posey.

Mr. POSEY. Thank you very much, Mr. Chairman, and I thank all of you on the panel for this very informative session, all of you.

Dr. Chang-Diaz, I was particularly pleased that you mentioned survival of our species as an important aspect of our space missions. I don't think that's emphasized enough. For a number of years, I know anytime any of us mentioned it, critics said you're trying to scare people into supporting space, and a lot of those critics dropped off a year or so ago when that relatively small, undetectable asteroid detonated over an uninhabited area of Russia a thousand miles from the closest living person and still injured over a thousand people, and made them reflect a little bit more about the cause of the last Ice Age, the cataclysmic asteroid that hit the Yucatan peninsula.

But anyway, thank you for mentioning that. I wish we would all be more informed about it and mention it more often. I think the public would have an interest in that. Since there's no more shuttles for Bruce Willis to change the course of these things on, we'd be in a bit of a bind. The longest silence I ever heard in this place was when I asked three of our top-ranking space officials what would happen if we found a relatively small one, the size of the one that exploded over Russia, headed for the Big Apple and we had three days, and we never would have three days to do something about it. It's the longest silence I've ever heard in this Committee.

But anyway, having always been informed that there's no such thing as perpetual motion or a perpetual energy machine, I wonder if any of you would care to comment on the closest thing to it that you have ever seen.

Dr. CHANG-DIAZ. I mean, in our case, we deal with it every day, it's superconductivity. The magnet that produces the strong magnetic field that houses the plasma in the rocket is a superconducting magnet, and this magnet runs electricity through its windings with almost zero, absolute zero resistance. So in a sense it's like this current can keep going forever. It's almost like a perpetual motion machine. It is not. There is a tiny little bit of resistance that you have to deal with, and that comes out in the electric bill that you do have to pay to keep the magnet running. It's just about 100 watts but you do have to pay for that. And this is technology that's already in the field and we see it in hospitals. MRI machines are basically superconductors, and we want to improve that technology to the high-temperature superconductors, which are much cheaper, much more capable so that we can have MRI machines in ambulances and perhaps in field hospitals or clinics and something that really can be done that way. So this is the way space feeds back to our society.

Mr. POSEY. There's been some theories that some other folks may have harnessed isolated and focused magnetism in a way that would propel without sparks. What do you think about that?

Dr. CHANG-DIAZ. Well, I've seen a lot of fringe projects that promise to deliver tremendous results, but we're all scientists and we all believe in the scientific process that's in place where scientists vet these things and you have to do an experiment and measure and be able to prove to your peers that you are measuring the right thing, and after you've done that, then people believe you. But until you do that, it's all just smoke and mirrors.

Mr. POSEY. Do any of you foresee any advances or breakthroughs in battery storage capacity in the relatively near future?

Mr. CASSADY. Yeah, I think that's something we're working pretty actively right now. We just replaced the batteries on the Space Station with lithium ion, an upgrade from the nickel hydrogen batteries that were the primary technology available at the time we started putting the Space Station together, and so we have a group in our company that's always looking at the next battery wave that's coming ahead of where we are now. A lot of that's being driven by what you see across multiple industries including the automotive industry, laptop computers and things like that, but we're looking always for what's the next energy-efficient without the problems of some of the reactivity that you have in something like a lithium ion battery, and there's a lot of applications for that that are driving that including long-term undersea as well as space, so yes, sir.

Mr. POSEY. I was going to ask you about a form of hydrogen but I'm about out of time and——

Chairman BABIN. No, sir. I'm going to take the liberty of the Chair and say we're going to ask some more questions. Go ahead. Finish.

Mr. POSEY. You know, when we talk about hydrogen that there's all kinds of hydrogen. During World War II we were having some disasters with some of our Navy frogmen, I understand. They'd be down there welding up a hole in a ship and their mask would explode, and it's my understanding that it was finally determined that the bubbles from the welding that they're doing contained a hydrogen and very explosive, and that was causing the problems with their masks. I don't know if that's a fact. I've been informed that from several sources.

So I saw a person one time have a fish tank filled with water, a stream of carbon at the bottom of the tank, put a welding rod in there, ignited the carbon, and it continued to burn by itself, and it made bubbles, and he had like a bell jar on top, and the bubbles burst and he captured the hydrogen in the bell jar, and pumped it into a compressor. He just used like a diver's air tank, sealed it up, hooked it up to a little engine, started the engine. The engine ran off it for about ten minutes that I witnessed, could put my hand on the engine, could put my face on the exhaust pipe. It ran that cool, and I'd just like your thoughts on that. I mean, I perceived all kinds of things just from looking at that and all kinds of uses for it, and I'm just——

Dr. CHANG-DIAZ. Yeah, your—I think your description, it seems to me that it was electrolysis——

Mr. POSEY. Yes, yes.

Dr. CHANG-DIAZ. —was what was happening here, and it was producing just—it happens that the electricity and that spark that you were seeing was breaking the water molecules into oxygen and hydrogen, and so there must have been two streams of gas, one that he captured in the bell jar, which was hydrogen, but there was also oxygen coming out, and yes, in fact, in our company, we're very deep in the hydrogen economy. In my home country of Costa Rica, we're trying to deliver and produce hydrogen from water and solar and wind energy electrically to power transportation, to power cars and mostly urban buses and trains and so on. So it is very much here and now.

Mr. POSEY. The typical hydrogen that you might put in a balloon and the balloon would be flat the next day. So we put some of this in a balloon and it was still just about fully blown up for over a month, and I just thought maybe the bucky balls were different in there, they were thicker, bigger, and that would not have let them escape, but I imagine by now—and this was 20 years ago—I thought now we'd be seeing something like this in progress and making energy for it and running people's homes and over-the-road trucks, and I'm just surprised.

Anyway, I know my time's up now, Mr. Chairman. Thank you so much, Mr. Chairman.

Chairman BABIN. No, sir, I think he's into racing cars and I think he's trying to figure out some way to get an edge with hydrogen.

Mr. POSEY. You know, I did spend a day with Smokay Yunick before he passed away, the greatest automotive mind I think in American history, and Smokay's the one that said—I mean, we talked about it a long time. He scratched his head and he said—

I mean, it's just hydrogen but it's different than any other hydrogen I've ever dealt with here.

Thank you, Mr. Chairman.

Chairman BABIN. Yes, sir. Thank you, Mr. Posey.

There was just a couple more questions that I wanted to ask as well of a couple of you, and Dr. Walker, what are the largest technological challenges associated with the development of advanced in-space propulsion generally? What are we dealing with her? What are we having to overcome?

Dr. WALKER. So the largest technological challenge is time. So whatever everyone alluded to here is I need a lot of electricity so I can get my trip time down. What they're not saying is that that means those engines that we use have to last thousands of hours, so the engine has to be able to run for years, and so if there is some small, little process that's slowly eating away at that engine, I have to have a great experiment to catch that process so I don't build it into my final product. So for us, we have to have really great facilities so we can catch the little, slow, progressing physics that will eventually kill the engine.

Chairman BABIN. And you're still talking about electric propulsion and solar electric propulsion, right?

Dr. WALKER. That's correct.

Chairman BABIN. The slightest little flaw over a period of years and you have a destroyed engine and you're dead. You're dead in the water.

Dr. WALKER. Correct.

Chairman BABIN. Yeah. Okay. And then I wanted to also ask Mr. Gerstenmaier, extensibility is the concept that technologies developed in the near term be useful for future exploration as well. Extensibility prevents the development of dead-end capabilities. How is NASA ensuring that its investments in in-space propulsion technologies are extensible?

Mr. GERSTENMAIER. Again, kind of what we're doing is, we look at systems that we put together, so when we talked about the cislunar habitat or the Deep Space Gateway, that uses 12–1/2-kilowatt thruster technology. We think a lot of the things we saw for that 12–1/2-kilowatt thruster level can be then advanced and moved forward through things similar to the nested technology that Joe talked about a little bit and then you can advance that to the higher-level thrust, maybe 50-kilowatt thrusters, for the deep-space transport. So that technology we do around the Moon to allow us to maneuver the habitat to various locations, that same technology then can be advanced and pieces of it moved forward.

We're also not only doing that but then we're also investing in this brand-new technology, the things that two of the panel members here are looking at that's a different technology but it has tremendous potential for us, so we want to invest in those on the ground to look at things like running them for 100 hours, and that was part of our test plan, and that was to look at this life issue that was described by the panel. So we think we can do that, then if that comes online, then we can interject that technology into that next generation of spacecraft. So the idea is to look at what we're doing with each piece, look at the individual technology underneath it, the power systems that have to convert from solar arrays and bring that power level to the thrusters. That same power conversion technology is common no matter what the thruster itself does. So that technology is common. So we look for those areas, those common threads across multiple technologies that can be expanded or extended into other areas, and we don't end up with a technology that only supports one type of spacecraft and has no applicability to other spacecraft.

Chairman BABIN. I appreciate that. We're talking about faster velocities. How much faster? I mean, if we're talking about this type of propulsion, and put it in terms of those of us who are laypersons can understand. How much faster are we talking about here? Any of you if you'd like to chime in.

Mr. CASSADY. So I mentioned the architecture studies that we're looking at. We typically want to try to work on about a two-year cycle for Mars missions as you know. About every other year there's a favorable opportunity to leave. So what we do—when I mentioned that 100- to 200-kilowatt system power level, we are trying to time the launches of the cargo vehicles so that they will be there, have enough time to have that equipment in position before we launch the crew on the next opportunity so there's sort of a natural cycle there of about two years. If we don't have enough power, and for whatever reason the thruster technology isn't adequate or the power system technology doesn't give us the efficiency of the power transfer from the arrays to the thrusters, then we'd end up probably extending that by six months or a year. So then we're out of sync and we're not able to support the mission. So that's really the trade the way we look at it. It's fitting the longer transit time that the solar electric's going to take to the other mission constraints like when we're going to want to launch the crew and get them there so that everything lines up.

Chairman BABIN. Okay. Thank you.

And then one last question, Mr. Jurczyk. Future in-space propulsion may require enormous amounts of power beyond what solar power can feasibly provide. What kinds of other power technologies is NASA pursuing to meet increasing power demands in coming decades?

Mr. JURCZYK. Yeah, so right now we're focused on compact nuclear fission-based reactors targeted for surface power currently but we can evolve it to spacecraft power systems. So early next year in collaboration with DOE we're going to demonstrate a 1-kilowatt fission-based reactor at the Nevada Test Site that scales to 10 kilowatts. And then the other key technology that's part of that is the conversion technology. So that's going to use sterling cycle engine technology to convert the heat from the reactor to electrical power. There are other cycles that we need to look at too but that's going to be key to get the efficiency up to convert the heat from the reactor to electrical power and continue to advance that conversion technology. So we are working—your current efforts are focused on surface power but we're looking at how those technologies and systems are extensible for nuclear power for spacecraft.

Chairman BABIN. All right.

Mr. Bera?

Mr. BERA. I'll take advantage. I feel like a student in office hours with the professors here.

So thinking about this with regards to solar electric propulsion, Mr. Cassady, the further you get away from the sun, does the amount you can generate diminish?

Mr. CASSADY. Yes.

Mr. BERA. Okay.

Mr. CASSADY. Yes, and Anthony referred to that in his remarks. So we're falling off, it's roughly a factor of two out at Mars. If you look at the history of deeper space exploration with the exception recently of Juno, everything we've sent out further in the solar system has used some sort of either radioisotope or other type of nuclear power, and solar arrays are only going to be good probably for going between here and Mars. At that point, some point in the future as we start to go further out, especially with human-scale missions, we're going to need to have nuclear power developed.

Mr. BERA. And again, it's appropriate. You know, part of the reason why we can use nuclear when we're going further out is, we don't have human beings and obviously the exposure factor is different.

It's also accurate to think then, you know, so for us in the public, we see big launches and you see the big thrusts and so forth. That really is to break the gravity well. Once you're beyond the gravity well of Earth and you're in the vacuum of space—and I don't know, you know—I think of space as a vacuum but I don't know if it's a true vacuum. As you're accelerating, though, you're going to continue to accelerate. Is that not—are we thinking about that correctly?

Dr. PANCOTTI. Yes, that's correct. So part of what I was talking about, we're dominated by orbital mechanics, right? So if the chemical system is what I call in my initial argument was kind of the impulse and coast, and that's what we do with chemical systems. We apply a force and then we coast for a very long time so all of the orbits line up and we can get to our destination as efficiently as possible because with chemicals systems with low ISP, they're not efficient and we have to do that in order to rendezvous and make that approach.

When I was talking about going to very high power and very high ISPs, we can talk about doing direct burns where we turn the thruster on and we leave it on and we just pick our target, we aim directly towards it, and we go straight for it. In order to do that in a short time, you need a large power, megawatts' worth of power, a nuclear reactor-type power.

Mr. BERA. So you can—if you're continuously thrusting and burning, you can cut the time down?

Dr. PANCOTTI. Yeah. In fact, sometimes you can even eliminate the need to do a fly-by, which is sort of another lap around the sun, and for some missions, there's a lot of missions right now in the new frontiers proposals that are out there that are looking at solar electric for that reason just because the science return, the time frame that they can get it back is reduced dramatically for these principal investigators.

Dawn is another good example that was brought up earlier. The ability to directly fly orbit one body in the asteroid body and then depart and go to another body, that's unprecedented. We've never been able to do that. And Dawn actually, I believe I read this right, my friend John Brophy at JPL was telling me the total amount of impulse that Dawn provided to the spacecraft, the ion engines provided to the spacecraft, was greater than the Delta-2 rocket that launched it out of the gravity well, so that's just to give you some idea, and it was done with just a couple hundred kilograms of xenon that was onboard the spacecraft.

Mr. BERA. So we spent a lot of time talking about acceleration and so forth but we also then have to think about deceleration, right? Do you have to use propellant to decelerate or do you through science use the natural gravity and atmosphere?

Mr. JURCZYK. Missions now use propellant to decelerate to say, achieve Martian orbit. There are other approaches that we've studied like aerocapture so you can dip down into the Martian atmosphere and use atmospheric drag to decelerate and then come back out and achieve Martian orbit. So there are other approaches that do not need propellant. But we haven't tried any of those yet, and I'd be really looking forward to a mission that would be willing to sign up for aerocapture. We do aerobraking right now where we go into Mars orbit in a high elliptical orbit and then dip down in the atmosphere to slow down and circularize the orbit but we haven't done aerocapture yet.

Mr. BERA. And then I guess my last question, one that I hadn't necessarily thought about, we've talked about what powers the engine, the propellant, the gasoline in that engine, and just again listening to the conversation, different propellants require different size gas tanks in essence, and right now are we also doing research on smaller propellants as well?

Mr. CASSADY. So there's a number of sort of lower technology readiness level things out there that people are looking at, especially now. I mentioned the constellations of satellites earlier. A lot of those constellations want to fly electric propulsion onboard a very small spacecraft, you know, maybe something that would sit on this table in front of me here, and for them, xenon, while it's good, it has some of the problems that you brought up—it needs a big tank of some sort—and they're looking at things that might be able to fly with a solid propellant, for instance, something like iodine and then let that propellant just sublime off into a gas and be run through the engine. So there are some programs like that I know that are out there and people are looking at.

Mr. JURCZYK. Just to add, we have several public-private partnerships within STMD, not only with our programs but also SBIR to advance these very highly efficient, very compact electric propulsion systems for cube sats and small spacecraft, and that's come along pretty well. Iodine—solid iodine is definitely one of the propellants that you can get the energy you need in a very small package.

Mr. BERA. Great. Thank you.

Chairman BABIN. Thank you, Mr. Bera.

And Mr. Posey has some additional questions.

Mr. POSEY. Just since we have the extra time, Mr. Chairman, if nobody minds.

As you know, we're still waiting on a map to Mars, a roadmap to kind of put everything in perspective, and so there's questions. We had the pleasure of asking today and learning the answers to today that maybe are a little bit ahead of the edge but we talk about the craft and the engines to take us to Mars, and we talk about the durability of them that's required, which is a serious issue, and I assume that we would use the craft and the engines continuously as much as possible. Once we would get them in orbit, we'd just have cyclers. We'd eventually have a supply train up there. Maybe we'd go back and forth to the Moon. I think Buzz Aldrin talked about it in his cyclers. You know, we ought to be able to get fuel on the Moon to go back and forth and refuel the cyclers and have stuff going all the time where if you were on Mars, you wouldn't have to wait two years to come home again, we'd have something going through there all the time. Thoughts about that?

Dr. PANCOTTI. Yeah, I can comment. I think what you're talking about is a truly sustained architecture. Those are the words we use a lot, a sustainable deep-space architecture. What we're talking about today is building the foundations to make that possible. With advanced power, in particular high ISP, which electric propulsion devices can do, you can start talking about building those infrastructures in space where you do have a continuous supply of materials.

Mr. POSEY. I think the NASA guys thank you for answering that. Thank you, Mr. Chairman.

Chairman BABIN. Is that it? Okay.

This has been a very fascinating hearing, one of the best ones that I believe I've had since I've been in Congress, so I'd like to thank the witnesses for being here and answering these questions, and I really, really appreciate your expertise in your fields, and without any further ado—let's see. Well, anyway we're going to have this thing opened up for a while to take any further questions or if any of the other Members who were not able to be here, if they want to ask further questions, they certainly can. It will remain open for two weeks for additional comments from our Members.

So without any further ado, I adjourn this hearing. Thank you.

[Whereupon, at 11:46 a.m., the Subcommittee was adjourned.]

Appendix I

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Mr. William Gerstenmaier

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"In-Space Propulsion: Strategic Choices and Options"

Mr. William Gerstenmaier, Associate Administrator, Human Exploration and Operations Directorate, National Aeronautics and Space Administration (NASA)

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. The National Academies' Pathways in Exploration report identified cryogenic propulsion, Nuclear Electric Propulsion, Nuclear Thermal Propulsion, and Solar Electric Propulsion as propulsion technologies "of greatest interest". The report added that "*As the technologies for in-space propulsion are developed and matured, there will likely need to be a down-selection among the four options due to the high development costs required for each one.*"
    a. Do you agree that avoiding the high development costs associated with maturing propulsion technology options could be achieved by moving to a down-selection acquisition strategy?

    Answer: In undertaking public-private partnerships, such as the Next Space Technologies for Exploration Partnerships (NextSTEP) effort, NASA's strategy is to avoid high development costs associated with maturing propulsion (and other) technology options. NASA, along with private sector partners, is developing solar-electric propulsion (SEP) capable of positioning future habitats, landers, and other elements in Mars orbit, and possibly deliver crew to Mars on a hybrid vehicle that also uses storable chemical propulsion.

    NASA is continuing to develop advanced Hall-effect electric thruster and propulsion technologies that could be used for the Deep Space Gateway concept, and are extensible to deeper space missions. NASA intends to examine, as part of NextSTEP, commercial spacecraft concepts at this power level as the initial element in a gateway as well as a future U.S. capability. As part of the NextSTEP effort, NASA is also evaluating higher-power electric propulsion technologies that offer the potential for substantially reduced transit times to Mars and other deep space destinations. These higher power technologies are in the early development stage, with several significant system development challenges that need to be addressed prior to being incorporated in an acquisition strategy and implemented on a NASA mission. Partners will demonstrate electric propulsion systems with higher specific impulse, higher efficiency, and higher power for long-duration deep space transportation systems and look at capabilities that are beyond those previously considered.

Cryogenic propulsion would be used primarily for mission phases that require high thrust, such as ascent from the surface of Mars. NASA does not currently expect to require nuclear thermal propulsion (NTP) or nuclear electric propulsion (NEP) in the initial crewed missions to the Mars system. Other advanced propulsion technologies, such as high-powered SEP combined with chemical systems, meet the needs of U.S. commercial aerospace industry while serving as the core capabilities for the initial in-space propulsion system for the Mars crewed missions.

b. If you do, how could such a down-selection be structured?

Answer: NASA's concept plans are to develop both a cislunar habitation capability and a Mars transit capability during the decade of the 2020s. To support estimated technology maturation and system development schedules for the transit vehicle, a downselect decision point would be targeted in 2020.

c. If you do not agree, how would you proceed and what would be the cost implications?

Answer: Please see response to Question #1b, above.

2. What are the key decision points for making commitments on in-space propulsion technologies? What has NASA learned about how to consider trade-offs among the technology options? To what extent are trade-offs dependent on the details of a mission? To what extent will the amount of time that crews are exposed to radiation influence NASA's decision on which technologies to pursue?

Answer: NASA's concept includes the development of a cislunar habitation capability and a Mars transit capability during the decade of the 2020s. To support estimated technology maturation and system development schedules for the transit vehicle, a downselect decision point is targeted in 2020. The results of NextSTEP concept developments using higher-power thruster technologies and the STMD nuclear thermal propulsion risk reduction activities will inform the design for the propulsion system of the Mars transit vehicle. By the end of the 2020s, this work will culminate in a one-year validation mission or "shakedown cruise" of astronauts aboard the transit vehicle that will verify that the propulsion system – as well as environmental control and life support systems – is ready for an interplanetary mission.

Mission design is a critical influence on trade-offs among technology options. In the area of propulsion, for example, chemical rockets provide high initial thrust and rapid acceleration, but are not very efficient, and cannot carry the fuel required to thrust continuously over interplanetary distances. Solar electric propulsion, in contrast, provides a low-thrust, but very efficient system which can operate for much longer periods of time, building up speed more slowly, but to a potentially higher final speed. Consideration of crew exposure to radiation will inform NASA's decisions about propulsion systems for crewed vehicles, possibly resulting in a hybrid chemical/SEP system that benefits from the advantages of both technologies.

3. Some space experts have advocated for using telepresence, where scientifically skilled humans work hand in hand from orbit with surface robots. These experts contend that more exploration could be conducted if it was not limited by astronauts operating on foot. In addition, by not landing on places like Mars, there would be less of a chance of introducing terrestrial contamination. The Gateway concept you introduced in March seems to provide opportunities for telepresence in exploration.
   a. What are the pros and cons of telepresence in NASA's human exploration strategy?

      Answer: NASA considers telepresence to be an important element of human space exploration. One example of this in low-Earth orbit is the extensive use of remote manipulators ("robotic arms"), in addition to astronauts conducting extravehicular activities (EVAs), first to assemble, and now to maintain the International Space Station (ISS). In the future, astronauts on a mission to orbit Mars or conduct operations on Mars' moon Phobos could benefit from a telerobotic presence on Mars itself, with the robot responding to commands from an astronaut in orbit or on Phobos. Having a human in the loop would improve the mission's ability to react to new discoveries and re-task the robot without inserting a lengthy communications time delay necessitated by Earth-to-Mars distances.

   b. What capabilities would the Gateway need in order to provide NASA and the commercial sector with the capability to test key systems needed for exploration through telepresence?

      Answer: The primary capability that a potential Deep Space Gateway would need to enable the crew to perform telerobotic operations on the lunar surface or in cislunar space would be a high data rate radio or optical communications system. The Gateway communications system would be used to transmit commands to telerobotic systems, to receive position and force feedback signals, and to provide high definition television for imaging the remote worksite. A virtual reality robotics workstation on the Gateway could enhance the crew's situational awareness, and enable real-time training by testing operational procedures before executing a task.

4. NASA recently announced that it is engaged in an "orderly closeout" of the Asteroid Redirect Mission. No longer funding the mission is being formally proposed in the Administration's FY 2018 NASA budget request. Under what authority is NASA closing out the mission in this fiscal year, FY 2017, since NASA's FY 2018 budget has not been appropriated?

Answer: Consistent with FY 2017 appropriations direction, formulation of the Asteroid Redirect Robotic Mission (ARRM) is discontinued; however, certain solar electric propulsion technology work is continuing.

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"In-Space Propulsion: Strategic Choices and Options"

Mr. William Gerstenmaier, Associate Administrator, Human Exploration and Operations Directorate, National Aeronautics and Space Administration (NASA)

Question submitted by Rep. Steve Knight, House Committee on Science, Space, and Technology

1. It's my understanding that NASA has been working with commercial lunar lander providers through the Lunar CATALYST program, which is leading to the development of the first robotic landers capable of making a soft landing on the lunar surface since the end of the Apollo program. In one case, your Space Technology propulsion experts at NASA have been working with industry partners like Aerojet Rocketdyne and one of the lunar lander companies, Astrobotic, to develop an ISE in-space propulsion system and test it on Astrobotic's first mission in 2019.

   Can you provide a little more background about how NASA is partnering with these companies to develop and test new in-space propulsion capabilities? Also, given that NASA issued an RFI for lunar lander services in last month, can you provide an update on NASA's plans to procure a mission on a commercial lunar lander over the next year or so?

   Answer: As part of NASA's effort to develop improved and lower-cost in-space chemical propulsion capabilities, the Agency has invested in a variety of technologies, such as engines that are very compact and that require much less electrical heating power to operate in space. NASA contractors in this area include Aerojet Rocketdyne, which worked with NASA in 2016 to conduct initial hotfire tests of its ISE-100 engine, and Frontier Aerospace, which is currently under contract to conduct engine development. The technology represented by these engines may eventually support various NASA missions, including lunar landers and solar system spacecraft.

   While NASA continues to mature a variety of propulsion technologies, the Agency is also supporting the development of commercial lunar exploration. In 2014, NASA introduced an initiative called Lunar CATALYST (Lunar Cargo Transportation and Landing by Soft Touchdown) and entered into competitively awarded partnerships with three U.S. firms (Astrobotic Technology, Masten Space Systems, and Moon Express) to provide in-kind support to develop commercial lunar robotic landing capabilities. NASA is providing engineering expertise, hardware and software, and test facilities to these companies. The purpose of the initiative is to encourage the development of U.S. private-sector robotic lunar landers capable of successfully delivering payloads to the lunar surface using U.S. commercial launch capabilities. Initial flights of commercial lunar landers may begin as early as 2018, and as a result one or more of these companies will be able to market lunar payload delivery services for small instruments and technology demonstrations. Commercial lunar transportation capabilities could support science and exploration objectives such as sample returns, geophysical network deployment, resource utilization, and technology advancements.

Responses by Mr. Stephen Jurczyk

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"In-Space Propulsion: Strategic Choices and Options"

Mr. Stephen Jurczyk, Associate Administrator, Space Technology Mission Directorate, National Aeronautics and Space Administration (NASA)

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. The National Academies' Pathways in Exploration report identified cryogenic propulsion, Nuclear Electric Propulsion, Nuclear Thermal Propulsion, and Solar Electric Propulsion as propulsion technologies "of greatest interest". Do you agree that these four technologies should be of greatest interest to NASA at this point in time? If so, what is NASA doing to pursue these research priorities?

   Answer: NASA concurs that these four propulsion technologies are of greatest interest to NASA, with one possible addition.

   - Cryogenic propulsion – this is a mature chemical propulsion technology where our primary research efforts are to improve the ability to store the super-cold cryogenic propellants for long periods in space.
   - Nuclear Electric Propulsion – this would employ extremely high power electric thrusters (several hundred kilowatts to mega watt) driven by electricity generated by a nuclear reactor. Space-based nuclear reactor technology is the main focus of our current research efforts along with work on higher power electric thrusters.
   - Nuclear Thermal Propulsion – uses the energy in a nuclear reactor to directly heat cryogenic hydrogen propellant. Our research is completing the second year of a three-year risk reduction activity focused on developing low enriched uranium (LEU) fuel elements, reactor design, and engine design including cost and schedule estimates. These activities are critical to establishing the technical and programmatic viability of developing a nuclear thermal propulsion system based on a LEU fueled reactor. In addition, the research efforts mentioned above on long-term storage of cryogenic hydrogen propellant is an essential part of the nuclear thermal propulsion research activities.
   - Solar Electric Propulsion – uses electricity generated by solar cells/panels to drive electric thrusters. Our research is focused on developing electric thrusters at several power levels, including development of Hall thrusters to support a ~50 kW spacecraft for human and robotic exploration.

   One possible addition to this list would be Hybrid Solar Electric/Chemical Propulsion which combines the benefits of high efficiency electric propulsion with the higher thrust and acceleration of chemical propulsion. All of our current research efforts on chemical and electric propulsion will contribute to advancing hybrid systems as well.

2. To what extent could NASA R&D on in-space propulsion systems benefit commercial industry or other potential users of the technology? What non-NASA applications might be made possible by the technologies we discussed at the hearing?

   Answer: The most important non-NASA uses of in-space propulsion are in delivering and maintaining satellites in their proper orbits for communications, weather forecasting, Earth observation, navigation and other critical purposes. The research that we are doing for in-space propulsion is providing new non-hazardous chemical propulsion systems and far more efficient electric propulsion systems to improve the performance and reduce the cost of these space operations. In the future, commercial development of cis-lunar space and utilization of interplanetary resources could be enabled by this propulsion technology, in particular by solar electric propulsion.

3. NASA issued its In-Space Propulsion Technologies Roadmap in July 2015.
   a. How has this document guided NASA in prioritizing the work needed to mature promising technologies and in establishing investment decisions? Are you still following it?

      Answer: NASA use the Space Technology Roadmaps, in this case the In-Space Propulsion Technologies Roadmap, as an initial, broad outline of all the important in-space propulsion related technologies that could be developed to support future space exploration activities. Resource limitations prevent the Agency from investing in all the technologies outlined in the Roadmap document. The Roadmap is one of many internal and external reports and inputs NASA uses to prioritize our in-space propulsion technologies investments. Currently, NASA is making the appropriate investments in Solar Electric Propulsion, Nuclear Thermal Propulsion, Nuclear Electric Propulsion, and Cryogenic Fluid Management, which are technologies outlined in the Roadmap.

   b. What are the Space Technology Directorate's next steps regarding this Roadmap? For example, do you plan to update the Roadmap? If so, when?

      Answer: STMD incorporates the Roadmap and inputs from our key customers and stakeholders in determining which in-space propulsion technologies are near-term priority investments. Currently, STMD is also developing a Strategic Implementation Plan (SIP) which incorporates inputs from the Roadmap. STMD will publicly release a draft of its SIP in September 2017.

      The Office of the Chief Technologist (OCT) is responsible for updating all the Space Technology Roadmaps on a regular basis. Currently, OCT is conducting a survey of key stakeholders to determine the future steps and content of revising the Roadmaps.

c. How are the Science Mission Directorate and the Human Exploration and Operations Mission Directorate working with you to establish the timeframes during which advanced propulsion technologies will be needed to support their projected missions?

Answer: STMD meets routinely with both the Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) to coordinate future mission and/or architecture technology and capability requirements along with potential timeframes. These inputs are then incorporated into STMD's strategic planning and prioritization framework and projected available resources to develop our current and future technology portfolios. Additionally, both SMD and HEOMD actively participate in the proposal evaluations and selections to ensure their mission needs are being met.

4. I understand that your directorate is examining Nuclear Thermal Propulsion (NTP) technology due to its potential to significantly reduce the time it would take to send astronauts to Mars and return them safely home. Reducing mission duration is important because it would cut the crew's exposure to galactic cosmic rays and other dangerous deep-space radiation. I am aware that NTP is also of interest to NASA because of the possible use of low enriched uranium (LEU) as nuclear fuel.

a. What is the current level of activity associated with Nuclear Thermal Propulsion?

Answer: Within STMD, there are currently multiple NASA-led projects that are developing key elements of an NTP system. The largest projects are devoted to developing LEU-based fuel elements for the reactor and cryogenic fluid management (CFM) technologies for long term storage of the liquid hydrogen propellant. The NTP project aims to design, manufacture, and test an LEU fuel element that meets NTP reactor performance requirements. The project is also determining the feasibility and affordability of an LEU-based NTP system to establish whether it is a viable alternative for crewed Mars missions. The most noteworthy objective of a project called eCryo in this context is a large-scale ground demonstration of liquid hydrogen storage with very low boil off of the propellant.

b. What has NASA learned to date about the possible use of LEU for an NTP?

Answer: NASA is collaborating with BWX Technologies and the Department of Energy to develop fuel element and reactor designs that utilize low-enriched uranium. The next progress review of that effort is in September 2017. A goal of the current NASA-led NTP project is to determine, by the end of FY18, the feasibility and affordability of an LEU-based NTP system in the thrust range of interest for a crewed Mars mission.

c. What are the technical and operational barriers to using an LEU-fueled NTP for a crewed Mars mission?

Answer: The main technical challenge for an LEU-fueled NTP system is designing compact fuel elements that meet the stringent requirements of thermal stability at high temperatures and mechanical stability over a wide range of operating temperature, low thermal neutron absorption and chemical compatibility. Unenriched uranium is about 99 percent U-238, which is non-fissile. Typical highly enriched uranium (HEU) fuels have enrichment levels of about 90 percent fissile U-235, whereas LEU fuel has no more than 20 percent U-235. Achieving the same performance with LEU as can be obtained with HEU requires the same number of U-235 atoms. Increasing the size of the reactor is one way to accomplish that, but the propulsion system thrust-to-weight ratio would be unacceptably high. The other approach to achieving the same overall U-235 loading is to design fuels with a much higher uranium density, which leads to materials and manufacturing challenges that must be resolved. The uranium must be alloyed with other elements to survive the reactor operating conditions, and there are very few viable choices.

d. What will be needed to enable use of NTP to support NASA's timetable of crewed missions to Mars in the 2030s?

Answer: The current NASA-led NTP project is aimed at designing, manufacturing, and performing initial testing of an LEU fuel element that meets performance requirements. Additionally, the project will determine the overall feasibility and affordability of an LEU-based NTP system for a crewed Mars mission. To enable use of NTP for a crewed mission to Mars, the next project would need to focus on accomplishing a subscale integrated engine simulator test, along with developing preliminary designs for the full-scale reactor and engine. The subsequent major step would be completing the design and building the reactor and engine, culminating in a full-scale, full-power engine test. During the course of these efforts, a ground test approach for capturing the exhaust would need to be developed and implemented. Additionally, long-term space storage of liquid hydrogen would need to be demonstrated, utilizing cryogenic fluid management (CFM) technologies that are currently being developed. The last major step would be to design and build the space propulsion stage that would utilize the NTP system and the CFM technologies. Affordability is likely to be a huge challenge for an NTP system. Until we have more information about the feasibility and affordability of an LEU-based NTP system, it is unclear if NTP could be used for a crewed Mars mission in the 2030s.

5. Under the NERVA program, engines tested on the ground were said to have met nearly all of NASA's specifications, including thrust and engine restart. Some historians believe that the lack of national support for undertaking a human mission to Mars contributed to NERVA's termination in 1973.
   a. Now that a human mission to Mars has been established as a goal, most recently in the 2017 NASA Transition Authorization Act, is it time to reexamine the applicability of nuclear propulsion for space travel?

      Answer: While higher power, higher thrust propulsion systems could reduce trip time and thus reduce risk to crew due to exposure to the deep space environment as well as reduce the transportation logistics burden, NASA does not require advanced propulsion technologies such as NTP in the initial crewed missions to the Mars system. Nuclear propulsion is likely to be very expensive to develop. Other advanced propulsion technologies such as high-powered solar-electric propulsion (SEP) or electric propulsion (EP), combined with chemical systems, meet the needs of U.S. commercial aerospace industry while serving as the core capabilities for the initial in-space propulsion system for the Mars crewed missions.

   b. If you don't think now is the right time, why not, and what is preventing nuclear propulsion from being considered in NASA's human exploration plans?

      Answer: High cost, long development times, and a lack of utility for US commercial providers are preventing nuclear propulsion from being considered in NASA's near-term exploration plans. However, the Agency is working on the technology for potential future applications. An Advanced Exploration Systems (AES) activity was initiated in 2012 to develop and test reactor fuel elements, a critical nuclear thermal propulsion (NTP) technology development challenge. This work was transferred from AES to the Space Technology Mission Directorate (STMD) at the end of 2015. The ongoing STMD nuclear thermal propulsion research is completing the second year of a three-year risk reduction activity focused on developing low enriched uranium (LEU) fuel elements, reactor design, and engine design including cost and schedule estimates. These activities are critical to establishing the technical and programmatic viability of developing a nuclear thermal propulsion system based on a LEU fueled reactor. In addition, the research efforts mentioned above on long-term storage of cryogenic hydrogen propellant is an essential part of the nuclear thermal propulsion research activities. These activities are the essential first step in determining the applicability for future exploration. At the conclusion of this three-year activity, a determination will be made whether to continue to pursue development of the nuclear thermal propulsion technology. If continued, the next project would need to focus on accomplishing a subscale integrated engine simulator test, along with developing preliminary designs for the full-scale reactor and engine. The subsequent major step would then be completing the design and building the reactor and engine, culminating in a full-scale, full-power engine test. During the course of these efforts, a ground test approach for capturing the exhaust would need to be developed and implemented. The total cost of the full scale, full power engine test along with the development of an operational NTP system, would be significant barrier in considering NTP for future human exploration missions.

Additionally, long-term space storage of liquid hydrogen would need to be demonstrated, utilizing cryogenic fluid management (CFM) technologies that are currently being developed. The last major step would be to design and build the space propulsion stage that would utilize the NTP system and the CFM technologies.

NASA has created an exploration architecture that would allow new technologies to used when the technology and cost challenges are developed and understood.

6. Regarding Nuclear Thermal Propulsion, the National Academies stated in its Pathways to Exploration report that key facilities and personnel from the NERVA program are no longer available and that it would be difficult to produce a test facility that could contain the propulsion exhaust of a full-scale NTP system.
    a. If NASA were to pursue Nuclear Thermal Propulsion, is there a way to recapture the experience from the NERVA program so that today's engineers do not need to start from scratch?

       Answer: All of the reports and data from the NERVA program have been examined in extensive detail by the current teams of scientists and engineers pursuing NTP development. Additionally, several of the NASA and Department of Energy team members were mentored at various points in their careers by personnel who were directly associated with the NERVA program. The advancements made and the lessons learned by the NERVA project are being directly incorporated into current NTP development projects.

    b. Could the use of a computational simulation facility reduce the extent to which a test facility is needed?

       Answer: Computer simulations are an important element of any propulsion system development effort, and NTP is no exception. However, the only way to determine the validity of models is by anchoring them to actual test data. For advanced propulsion systems that are improvements on existing implementations or entirely new approaches, the models must be modified and extended, which requires still more test data. Because there has been no NTP testing in about 45 years, some testing is needed to reacquire the knowledge on how to operate such a system safely and efficiently. In addition, no propulsion system of any type is typically flown without extensive qualification testing to ensure that it meets performance requirements in the most demanding operational environments it will experience in flight. In the propulsion realm, where testing can be quite expensive, modeling is always used to limit the number of tests to the essential minimum. Any NASA-led NTP project would certainly use modeling to the greatest extent possible due to the difficulties and cost inherent in testing a nuclear system.

7. In their prepared statements, Dr. Walker and Dr. Pancotti referred to the need for enhanced testing capabilities and facilities at NASA Centers.
   a. Do you agree that additional testing facilities and capabilities are needed at NASA Centers to enable testing of thrusters with higher power levels? If you agree, what is the impact of the absence of enhanced testing capabilities on the pace of progress on developing in-space propulsion technologies? What can be done to preclude this from happening?

      Answer: The capability needed in a test facility for an electric propulsion (EP) thruster depends heavily on the characteristics of the device. There are several different categories of EP thrusters with a wide range of characteristics, including different operating modes (such as pulsed or continuous) and different types of propellants. To perform extensive testing on the types of 100 kW class thrusters currently under development, the largest NASA test facilities would require some enhancement to increase vacuum pumping capability. However, such thrusters are currently at a relatively low technology readiness level, so the need to augment current test capabilities is not urgent.

   b. If you do not agree, what is the basis for your position?

      Answer: Please see response to question 7a.

Responses by Dr. Mitchell Walker

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"In-Space Propulsion: Strategic Choices and Options"

Professor Walker, Professor and Educator, Georgia Institute of Technology

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. In your opinion, are advanced in-space propulsion technologies needed to enable a humans to Mars mission in the 2030s? If so, what R&D strategy will be needed to mature the technologies? Which technology do you feel is the one needed to get humans to Mars and why? Based on NASA's resources currently allocated to developing advanced propulsion technologies, are we likely to achieve the 2030s target date? If not, what is the level of investment needed?

   Answer: Several studies show that existing in-space chemical propulsion technology possesses the performance to enable a humans to Mars mission in the 2030s. From a budgetary perspective, advanced in-space propulsion technologies are critical to enable a humans to Mars mission in the 2030s because the performance characteristics of these technologies dramatically reduce the total mission cost and risk. In particular, the use of contemporary chemical propulsion technologies to travel from Earth to Mars requires a significant quantity of propellant because of the limited specific impulse of chemical propulsion. To place this quantity of propellant in orbit requires multiple launches of a large launch vehicle in a relatively narrow window of time. Each of these launches adds considerable cost and risk to the successful completion of the mission. The high specific impulse of advanced in-space propulsion substantially reduces the amount of propellant required to travel from Earth to Mars with a commensurate reduction in the number of required launches, cost, and risk to humans to Mars mission.

   The payload of a humans to Mars mission consists of humans as well as the necessary infrastructure and consumables to keep them alive. Humans will travel from Earth to Mars in a vehicle that uses high-thrust propulsion, *i.e.*, chemical propulsion. The high thrust levels minimize the length of the mission to reduce the health threats from exposure to the deep-space environment and to minimize the consumables required in their vehicle. The high specific impulse and power-limited thrust levels of advanced in-space propulsion technologies will take many months to years to propel a spacecraft from Earth to Mars, but these characteristics work well for missions that deliver infrastructure and consumables to Mars in anticipation of the arrival of humans. Thus, a robust strategy for a successful human to Mars mission combines the strengths of chemical propulsion and advanced in-space propulsion technology.

In my opinion, Hall effect thrusters and gridded ion are the most mature technologies to scale to the power levels required to place the infrastructure and consumable supplies on Mars to support the human to Mars mission in the 2030s. This opinion is based on the demonstrated success of these propulsion technologies on NASA deep-space missions (NSTAR and DAWN) and all-electric satellite platforms. As the required power level of the individual thrusters grows, the Hall effect thruster shines because of its high thrust density and demonstrated scalability.

The successful maturation of these technologies hinges on two activities. One, we must build two or more national-level vacuum facilities that possess the capability (pumping speed, thermal management, backsputter levels) to perform high–fidelity R&D on high-power (100 kW) electric propulsion devices. Two, we must make a sustained investment in university research laboratories to ensure that a robust talent pool exists to execute a human to Mars mission in the 2030s. Based on my knowledge of existing investments, an order of magnitude increase is required in our investment in advanced in-space propulsion technologies, test facilities, and the work force pipeline.

2. To what extent could NASA R&D on in-space propulsion systems benefit commercial industry or other potential users of the technology? What non-NASA applications might be made possible by the technologies we discussed at the hearing?

   Answer: NASA R&D is poised to provide the critical technologies, physical infrastructure, and understanding of unique physical processes to enable U.S. industry as well as DoD agencies to continue harness the benefits of in-space propulsion systems. Industry and DoD agencies execute Earth-centric spacecraft missions that enhance economic activity and security. These users made a clear shift to hybrid (chemical apogee engines with electric propulsion stationkeeping) and all-electric spacecraft because of the economic benefits provided by the architectures. The electric propulsion technologies harnessed on all-electric spacecraft evolved from stationkeeping requirements. Future electric propulsion technologies will need to be tuned so that users in industry and DoD agencies extract greater benefit from all-electric architectures. In particular, these users place a premium on technologies that reduce the time required to perform a particular maneuver, *e.g.*, the GTO-to-GEO transfer and stationkeeping. Thus, these users require significant increases in the thrust-to-power (*T/P*) ratio of electric propulsion technologies.

   NASA R&D is uniquely positioned to build an understanding of the physical processes that currently limit the *T/P* ratio of electric propulsion technology and thus pursue the leading opportunity in electric propulsion technology for these users. This activity may include the development of new diagnostics and understanding that aid NASA missions. In addition, the results of the NASA R&D portfolio will enhance the performance of electric propulsion technologies over a broad range of operating conditions and continue to shed light on thruster lifetime limitations. Furthermore, NASA R&D can lead to the critical flights that are required to enhance our ability to extrapolate the performance and operational characteristics measured in ground-based vacuum facilities to the space environment. These results reduce risk in missions flown and proposed by industry and DoD agencies.

The non-NASA applications that might be made possible by the technologies we discussed at the hearing are broad. In my opinion, the most immediate applications are related to high-power tugs for placement and removal of assets in GEO as well as servicing/refueling missions. This assumes the requisite spacecraft power is available to operate these 100+ kW technologies.

3. In your prepared statement you state that investment in ground-based facilities is one of the top activities that will bolster U.S. leadership in solar electric propulsion technology. You also state that as the power level of electric propulsion devices continues to grow, the demand on vacuum test facilities will increase. Can you talk more about the need for more capable ground-based testing facilities and why you think existing facilities are inadequate? Is industry prepared to make use of such facilities on a reimbursable basis?

   Answer: The VF-5 test facility at NASA Glenn Research Center has the highest performance (pumping speed) of any vacuum facility devoted to electric propulsion in the United States and arguably in the world. VF-5 has an upper power limit for high-fidelity operation of electric propulsion devices in the range of 15-20 kW. This statement is based on the consensus of the electric propulsion community for thruster characterization, documented in the American Insitute of Aeronautics and Astronautics electric propulsion test standards.[1] The VF-5 test requires an order of magnitude increase in vacuum pumping speed to perform high-fidelity performance characterization of the 100+ kW devices funded in the NextSTEP program.

   Furthermore, there are only two other electric propulsion vacuum facilities in the United States that approach the capability of the VF-5 test facility. Thus, if the VF-5 test facility is occupied with NASA R&D activities or down for routine maintenance, commercial users have few options for places to perform high-fidelity development and qualification of 10-15 kW electric propulsion devices.

   Industry is prepared to make use of electric propulsion test facilities on a reimbursable basis to perform high-fidelity testing as part of their R&D activities. Currently, industry meets its need for test facilities by renting facilities at The Aerospace Corporation, NASA, and University laboratories to meet their needs. Industry producers of electric propulsion devices have acquired in-house electric propulsion test facilities for acceptance testing of flight hardware before it is delivered to customers. The facilities are well-documented with highly-controlled test configurations. Simultaneously, an

[1] John Dankanich, Mitchell Walker, Michael Swiatek, John Yim, "Recommended Practice for Pressure Measurements and Calculation of Effective Pumping Speeds during Electric Propulsion Testing," Journal of Propulsion and Power, Volume 33, Number 3, May-June 2017, pp. 668-680.

industrial supplier or user of electric propulsion must have a "research facility" for enhancement of existing product lines, development of new product lines, additional characterization for new customers, and the ability to assist customers in on-orbit anomaly investigations that impact the propulsion system. In response to the need for separate acceptance and research electric propulsion facilities, many industry financial models rent existing facilities to fulfill their need for a "research facility" without bearing the cost of their physical infrastructure. Thus, industry already makes uses of electric propulsion test facilities on a reimbursable basis. In my opinion, industry would welcome the availability of one or more national-level electric propulsion test facilities.

4. In your prepared statement you state that "*electric propulsion will be part of the solution to our growing space debris challenge.*"
   a. Does mitigating space debris depend on advancing electric propulsion technologies? If so, which advances are needed in the near term?

      Answer: In my opinion, mitigating space debris does not depend on advancing electric propulsion technologies. The removal of space debris requires a propulsion system that operates with high specific impulse. This maximizes the change in the trajectory of large pieces of debris per kg of propellant expended. Many existing electric propulsion technologies are sufficient to make a significant reduction in the space debris population.

   b. Do other propulsion systems such as nuclear thermal or chemical propulsion have a role to play?

      Answer: Nuclear thermal systems typically have an advertised specific impulse less than 1,000 s. High-performance chemical propulsion systems have a specific impulse of approximately 450 s, with storable propellants delivering a specific impulse less than 330 s. The specific impulse of nuclear thermal and chemical propulsion is not competitive with electric propulsion technology in space debris removal applications. Furthermore, the larger thruster levels of nuclear thermal propulsion and chemical propulsion are not advantageous nor required in debris removal applications.

5. In planning for the proposed Gateway and Deep Transport space vehicles, NASA will face a major decision on whether these future space vehicles will be propelled using a set of multiple solar electric thrusters or a lesser number of more powerful solar electric thrusters. What key factors should NASA include while conducting a trade-off analysis between these two options? At this point in time, is enough known about each of the options to mitigate projected technical and operational risks? If not, how should that needed knowledge be secured?

<u>**Answer**</u>: The system trade-off between clustering multiple small solar electric thrusters and few large thrusters solar electric thrusters is always under discussion in the in-space propulsion technical community. The U.S. Air Forces investigated this question in detail in the early 2000's with a host of thruster performance-focused research efforts. The presumed goal of clustering thrusters is to achieve a propulsion system with a total power significantly greater than the nominal power of any thruster that could be tested in a ground-based vacuum facility. In theory, there are many advantages to this approach related to scaling, cost, and manufacturing. In practice, the design of the cluster of thrusters introduces many variables that can have unforeseen consequences on the operation of the individual thrusters, the mass efficiency of scaling to high power levels, redundancy, systems complexity, and integration with the spacecraft.

In my opinion, the following questions must be addressed:

1. What is our confidence in our ability to extrapolate the performance of a single thruster to the performance of a cluster? While a few percent change in performance or plume properties may not impact the total system, changes in the thermal behavior, life time, and electrical operational characteristics could be significant to the development program. Currently, we do not know enough about this item to mitigate projected technical and operational risks. A physics-based understanding of clustering of thrusters is needed. To create this knowledge requires a combination of numerical and experimental investigations performed through a collaboration between government labs and universities.
2. What is the predicted available electric propulsion test facility capability in the near future (5-10 yrs)? The size of these facilities will set the maximum power of a single thruster element in the cluster. Based on the mass efficiency of the proposed cluster, *i.e.*, the duplication of many components common to each thruster, the maximum total system power can be defined.
3. What is the predicted thruster power needed for industry and DoD agencies users? The ability to leverage the needs of many users will impact the development cost of the element thruster.
4. What is the predicted cost to flight qualify the thruster element? The cost for facility operation and consumables (propellant and liquid nitrogen) may set the upper limit on the size of the thruster element.

Responses by Dr. Franklin Chang-Diaz

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"In-Space Propulsion: Strategic Choices and Options"

Dr. Franklin Chang-Diaz, CEO, Ad Astra Rocket Company

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. In your opinion, are advanced in-space propulsion technologies needed to enable a humans to Mars mission in the 2030s? If so, what R&D strategy will be needed to mature the technologies? Which technology do you feel is the one needed to get humans to Mars and why? Based on NASA's resources currently allocated to developing advanced propulsion technologies, are we likely to achieve the 2030s target date? If not, what is the level of investment needed?

Answer:

a) A human mission to Mars is possible with today's technology. However, such a mission would be extremely fragile, expensive, and a follow-on program would be economically unsustainable. Advanced in-space propulsion technologies are needed to achieve a robust and economically sustainable human exploration program of Mars and beyond.

b) To mature these technologies, our R&D strategy needs high-power electric propulsion (EP). High power starts at hundreds of kW (the power of a medium 5-passenger SUV) and extends up to tens of MW (the power of a commercial airliner). Initially, the low-end (hundreds of kW) of the power range could be achieved with solar energy as solar electric propulsion (SEP). The upper end of the power range (megawatts), needed for human transport, will require nuclear electric propulsion (NEP) with electricity from a nuclear reactor. For human deep space exploration, NEP is essential. Sunlight fades quickly as we move away from Earth and the Sun ceases to be useful as a robust power source.

c) High power electric plasma rockets, such as the VASIMR® engine, are best suited for this type of space transportation.

d) These rockets scale naturally from 100 kW to multi megawatts and can be driven by electric power from both solar or nuclear sources. They also utilize widely available and economical propellants, such as argon ($5/kg) vs other electric rockets operating on xenon ($1000/kg). The VASIMR® engine has already demonstrated ideal performance in thousands of ground-based tests (power efficiency, thrust and specific impulse) for Mars journeys at power levels of more than 200 kW (in a single unit).

e) No, with current NASA advanced propulsion resources, we are unlikely to achieve the 2030 human Mars landing target.

f) The VASIMR® engine is now sufficiently mature (achieving TRL-5 in 2018) to warrant a rapid development effort to a flight demonstration (TRL-6). The level of financial investment needed for this demo is approximately $300M over 3-4 years, including the launch and the spacecraft carrier. This effort will enable the technology to be commercialized. Additional private investment can then continue to refine the technology in support of commercial solar electric propulsion (SEP) applications in the Earth-Moon environment. These include, satellite deployment, servicing, repositioning, refueling, orbital debris clean up, space station re-boost, among others.

2. To what extent could NASA R&D on in-space propulsion systems benefit commercial industry or other potential users of the technology? What non-NASA applications might be made possible by the technologies we discussed at the hearing?

<u>**Answer**</u>: Because of their extremely frugal fuel consumption, about 1/10 of conventional chemical rockets, high power electric propulsion leads to increased payload capacity for a given launcher and hence lower cost. "SEP space trucks," strategically parked in orbit, could service the needs of the growing satellite market, including deployment, repositioning and refueling. SEP space trucks can also help clean up orbital debris, a growing concern for satellite operators and space station astronauts. A SEP module, such as Ad Astra's *Ocelot*™ power and propulsion module, could also provide orbital re-boost to large space stations, such as the ISS at 1/20 the present cost. Our estimates show that the present chemical fuel delivery cost for ISS re-boost exceeds 200 M$/year. This number could be reduced to roughly 10 M$/year. Other applications include propelling fast robotic instrument packages deep into the solar system and supporting the potential growth of in-space mining.

Other than in-space propulsion, plasma technology has many revenue-generating earth-bound applications in medicine, microelectronics, materials processing and energy. Related technologies to plasma electric rockets, such as superconductivity and radiofrequency (RF) power are used in MRI devices, communications, transportation and power generation and transmission.

3. In planning for the proposed Gateway and Deep Transport space vehicles, NASA will face a major decision on whether these future space vehicles will be propelled using a set of multiple solar electric thrusters or a lesser number of more powerful solar electric thrusters. What key factors should NASA include while conducting a trade-off analysis between these two options? At this point in time, is enough known about each of the options to mitigate projected technical and operational risks? If not, how should that needed knowledge be secured?

Answer: Key factors include:

a) *Scalability*: Does the physics of the engine allow it to scale from hundreds to thousands of kW per engine? A common approach when faced with physics limits on engine power is to cluster many of them together, arguing that doing so also increases redundancy and system reliability. Such reasoning has not been validated by experience. As we have seen in the aircraft industry, larger commercial airliners have not generally increased the number of engines but have evolved instead to fewer more powerful ones, reducing system complexity. The reliability and redundancy are achieved in the architecture of the engine itself.

   In the electric propulsion (EP) space, two technologies "shine" in different power ranges with a small overlap at about 50 kW. At power levels below 50 kW, the Hall Effect Thruster shows a clear advantage over the VASIMR® engine in terms of propulsion system mass. Above that value, however, the VASIMR® system is the better choice. The controlling physics of each technology are responsible for these trends. Hall propulsion systems have a lower power density, so engine clustering is required to reach high power. VASIMR® engines, on the other hand, have 10x higher power density and can grow in power at the engine level with only small increases in mass. For example, present-day Hall thrusters are being developed to operate a ~12 kW (the power of a small motorcycle) so approximately 17 of them are required to propel a 200 kW space truck. Instead, the same space truck could be propelled by two 100 kW VASIMR® engines (each the equivalent of a medium size car engine) or a single one at 200 kW. Clustering or not, extending the power range to multi-megawatts will ultimately require more powerful engines.

b) *Performance*: In a rocket engine, the key performance metric is the specific impulse (I_{sp}), which is expressed in units of "seconds" and is roughly equivalent to the gears in a car. In a car, higher gears are associated with higher speeds and low fuel consumption, while lower gears provide higher torque but consume more fuel. Rockets are similar; higher I_{sp} is associated with high speed and low fuel consumption, while low I_{sp} provides higher thrust but leads to high fuel consumption. Electric rockets in general have about ten times higher I_{sp} than chemical or nuclear-thermal rockets. Within the family of electric rockets, some have higher I_{sp} than others. The I_{sp} of a Hall thruster, operating with xenon, tops at ~3000 sec, while that of a VASIMR® engine, operating with argon is ~5000 sec. Conventional Hall thrusters are "single gear" engines, while VASIMR® engines can "shift gears," an advantage that translates in the lowest fuel consumption for a given mission.

c) *Access and cost of fuel:* In planning for a robust and sustainable human space exploration program, fuel availability and cost are also important factors. Hall thrusters presently operate with xenon, a rare and expensive (~1000 $/kg) gas. There is technology being studied to enable these thrusters to operate with krypton, a less rare and expensive

(~300$/kg) fuel. VASIMR® engines, on the other hand, operate with Argon, an abundant and inexpensive fuel (~5$/kg), as well as krypton, hydrogen and others. Both Argon and Hydrogen are available on Mars and are likely to be found throughout the solar system.

Some things are clear. High-power electric propulsion requires abundant space electric power; therefore, development of space electric power, both solar (SEP) and nuclear (NEP), needs to be vigorously pursued and funded. While the former is receiving some level of attention now, the latter is not. NEP is not to be confused with nuclear-thermal rockets, which are receiving some level of attention/funding now, but are not capable of the high I_{sp} needed for fast human travel in deep space. For human transportation, nuclear-electric space power, capable of driving multi-megawatt NEP, is essential. Our NEP know-how, however, has been stagnant for decades and the public lacks updated information. Contrary to popular belief, NEP reactors will not pose a threat to Earth, as the fuel will be transported in segmented, non-hazardous form to the vicinity of the Moon and the reactor assembled and started there. Notwithstanding its controversial nature, the nuclear-electric option is critical for us to seriously explore deep space with humans.

Electric propulsion, in its solar version (SEP), will play an increasingly important role in the commercial space logistics market in the Earth-Moon environment, but only a transitional role on robotic cargo vehicles out to Mars. At Mars distances, the robustness and performance of the nuclear-electric approach will quickly gain preference. Therefore, electric propulsion technologies must be naturally scalable from SEP to NEP and be examined in the context of the *key factors* discussed above.

In space, power and propulsion are the two most important technology challenges to insuring a sustainable and robust human space exploration program. They go hand-in-hand. and both need to be pursued in parallel vigorously and without delay.

- *Test in space, early and frequently to learn early in the technology maturation process when design flexibility still exits. This reduces the time to operational deployment of the technology.*
- *Utilize the ISS national laboratory as a developmental test bed for high power EP. Alleged ISS power limitations, often mentioned to dismiss these tests, can be easily overcome with energy storage devices, such as batteries.*
- *With proper design of the EP test, the thrust of the engine could provide an added re-boost benefit to the ISS, saving fuel and operational cost.*

Traditionally, low power EP technology has been developed in the laboratory and tested in Earth-bound facilities over very long duration qualification tests, leading to a very long development time. This was reasonable because low power EP test facilities are fairly inexpensive and numerous and the typical first flight of the EP technology would be part of a larger and expensive technology demonstrator spacecraft (v.g., Deep Space-1, Dawn,...) with critical mission objectives for many other equally important stakeholders besides the propulsion system. High power EP technologies bring a new set of drivers that point to a different paradigm.

First, the 100x increase in the power of these rockets implies a similar increase in the vacuum pumping requirement of the chambers where the rockets are tested, significantly increasing the cost and reducing the availability of suitable test facilities.

Second, the size of the exhaust jet is much larger, requiring much larger chambers to alleviate effects on the performance measurements caused by the proximity of chamber walls.

Third, Earth-bound EP thrust measurements are carried out on "thrust stands," highly sensitive mechanical structures, placed inside the vacuum chamber, that must eliminate all gravity-induced effects to extract a clean measurement. As the power of the rocket increases, so does the expense and complexity of the thrust stand. Today, these tests should migrate to the ISS national laboratory. A spacecraft itself, the ISS is an ideal "thrust stand" where performance of different EP technologies could be readily and unambiguously measured; moreover, in the nearly infinite vacuum of space the vacuum and chamber walls issues would be eliminated. With proper design of the ISS test, the thrust of the rockets could provide an added re-boost benefit to the orbital facility, saving ISS fuel and operational cost.

These considerations are relevant given our maturity as a space-faring nation. We have a human-tended national laboratory orbiting the Earth in the vacuum of space with astronauts executing increasingly complex scientific and technical tasks inside and outside of the spacecraft. Besides life sciences and microgravity experiments, we should use this capability for high power EP. Access to space is now more routine and less expensive. Early space testing allows us to also "tease out" performance and reliability issues associated with the space environment itself, which are difficult to model precisely in ground facilities.

Responses by Mr. Joe Cassady

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"In-Space Propulsion: Strategic Choices and Options"

Mr. Joe Cassady, Executive Director for Space, Washington Operations, Aerojet Rocketdyne

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. In your opinion, are advanced in-space propulsion technologies needed to enable a humans to Mars mission in the 2030s? If so, what R&D strategy will be needed to mature the technologies? Which technology do you feel is the one needed to get humans to Mars and why? Based on NASA's resources currently allocated to developing advanced propulsion technologies, are we likely to achieve the 2030s target date? If not, what is the level of investment needed?

   Answer: Advanced in-space technologies are strong enablers for NASA's human Mars mission. Electric propulsion will provide the capability to transport large, massive cargo to Mars in advance of human landings. Advanced propulsion technologies span a wide range of possible options. NASA has engaged with industry to develop a portfolio of potential solutions that include:

   - Hall thrusters scaled up from current flight designs (12.5 kW)
   - Nested Hall thrusters with capability to operate over power from 50 – 200 kW
   - More advanced EP designs such as pulsed plasmoid FRC or VASiMR
   - Nuclear thermal

   Current Mars architectures for human missions in the 2030s rely on Solar Electric Propulsion (SEP) systems in the 100 – 200 kW total system power range to transport and pre-deploy cargo and supplies to Mars. The 12.5 kW Advanced Electric Propulsion System (AEPS) thruster strings under development now by NASA STMD are a good fit for these cargo vehicles. Currently, the AEPS development is fully funded and on track to deliver flight thruster strings in the 2019 timeframe. What is missing is the demonstration mission for this technology. NASA has indicated the possibility of a lunar orbital mission of a 40 kW power and propulsion element as part of the Deep Space Gateway. It is important that an SEP system demonstration occur in the 2021/2022 timeframe to provide risk mitigation for the 100 – 200 kW cargo missions which would be launched as early as 2028. The level of investment required is likely much lower than the $1.5 billion estimated for the Asteroid Robotic Redirect Mission (ARRM) since there would be no requirement for robotic systems and operations around an asteroid. It is assumed that this mission would launch on the SLS EM-2 mission, so no additional launch costs would be incurred.

Longer term, as an outpost is established on Mars, it will be important to have regular efficient transport of crews and cargo between Earth and Mars. The systems to perform these functions will be higher power (greater than 500 kW) and will be well suited to the other propulsion options now under development by NASA. Nuclear thermal propulsion is also included in this category as a possible on-ramp technology to shorten crew transit times.

2. To what extent could NASA R&D on in-space propulsion systems benefit commercial industry or other potential users of the technology? What non-NASA applications might be made possible by the technologies we discussed at the hearing?

   Answer: NASA R&D on in-space propulsion such as the current Space Transportation Mission Directorate (STMD) AEPS program has direct crossover benefit to commercial and DoD satellite deployments. The higher power operation of these thrusters which is desired for Mars and cislunar cargo transportation also makes it possible to deploy large satellites into higher orbits around Earth more efficiently. Currently, this function is accomplished by chemical propulsion systems on the satellites themselves. In fact, a typical GEO satellite mass is approximately 50% propellant when dropped off by the launch vehicle. By using Electric Propulsion (EP) to perform the orbit transfer, the propellant mass can be reduced to a fraction of the chemical propellant mass. However, the trade-off is greatly increased time to reach the final operational orbit – months instead of days. Because communication satellites size their power systems to the payload power requirements (typically 8 kW – 15 kW) the power available to the EP thrusters is limited and this extends the trip time. With higher power EP systems (20 kW – 30 kW) dedicated to the orbit transfer function, trip times can be reduced by up to 50 % which is highly desirable for commercial and DoD users. It is critical to understand that for Earth orbital missions (GEO communications, MILSATCOM, GPS, SBIRs, etc) power levels for orbit transfer will not exceed more than 50 kW. Therefore, development of very high power EP devices is not required to support these applications.

3. In planning for the proposed Gateway and Deep Transport space vehicles, NASA will face a major decision on whether these future space vehicles will be propelled using a set of multiple solar electric thrusters or a lesser number of more powerful solar electric thrusters. What key factors should NASA include while conducting a trade-off analysis between these two options? At this point in time, is enough known about each of the options to mitigate projected technical and operational risks? If not, how should that needed knowledge be secured?

   Answer: The NASA architecture trades are considering two types of SEP transfer vehicles. The first would transfer only cargo between Earth orbit and lunar orbit, or Mars orbit. This vehicle is likely to require between 100 kW – 200 kW as I stated in my testimony. For a vehicle of this total power, it is not desirable to use a 100 kW EP thruster, as there are system design considerations (redundancy, control, and others) which favor using a larger number of thrusters. This was the rationale behind selecting 12.5 kW for the AEPS development program.

The second type of vehicle is represented by the Deep Space Transport (DST). The DST is envisioned to transport both crew and cargo to Mars from lunar orbit. As such, it would embody a much higher power SEP system power (400 kW – 500 kW) and therefore would require greater than 25 thrusters of the AEPS power level. While there are no hard and fast rules governing the choice between large numbers of thrusters and a smaller number of more powerful (e.g. 100 kW) thrusters, there are some commonly held principles of system engineering that do apply. For redundancy purposes and graceful degradation, it is usually good practice to employ a minimum of three and possibly a spare fourth thruster. Use of multiple thrusters can also provide a simpler way to deal with the change in power as the spacecraft moves between Earth (1 AU) and Mars (1.52 AU). As the spacecraft moves away from the Sun, the power falls off proportional to $1/r^2$ (where r equals the distance to the sun)so that the original power of 400 kW at 1 AU (Earth orbit) becomes approximately 175 kW at Mars orbit. Therefore, the SEP system must adapt to a power variation of more than a factor of two.

With many thrusters it is possible to shut down individual thrusters as the spacecraft moves outward to modulate the power. This is more easily accomplished with a larger number of thrusters (greater than 10). With a small number of higher power thrusters, the drop in individual power level (approximately 100 kW) is too high so some form of throttling must be implemented in the system design. Throttling impacts the design of both the power processor and the flow control system, because both power level and flow rate must be varied to maintain steady thruster operation at the various power set points.

The key factors that NASA needs to include in their trade off analysis include these general system engineering principles, together with technology readiness level (TRL) and manufacturing readiness level (MRL) of the options. It is critical that these assessments consider the entire system (thruster, PPU, and flow control) as well as any required ancillary hardware such as cryogenic storage systems if using hydrogen as a propellant.

The current plan for NASA's technology maturation includes the AEPS program (at 12.5 kW) and the NextSTEP program (at 100 kW). Each program includes near-term testing that will inform a selection decision for the Gateway and Deep Transport vehicles. The results of these tests should provide a valid basis for concept selection by early 2018.

Responses by Dr. Anthony Pancotti

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"In-Space Propulsion: Strategic Choices and Options"

Dr. Anthony Pancotti, Director of Propulsion Research, MSNW LLC

Question submitted by Ranking Member Ami Bera, House Committee on Science, Space, and Technology

1. In your opinion, are advanced in-space propulsion technologies needed to enable a humans to Mars mission in the 2030s? If so, what R&D strategy will be needed to mature the technologies? Which technology do you feel is the one needed to get humans to Mars and why? Based on NASA's resources currently allocated to developing advanced propulsion technologies, are we likely to achieve the 2030s target date? If not, what is the level of investment needed?

   Answer: I strongly believe that advanced in-space propulsion is a cornerstone technology for all future deep space activities. To mature any of these technologies, adequate funding, early NASA involvement and oversight, and larger testing facilities will be key to an effective R&D strategy. FRC technologies offer the most promising attributes for getting humans to Mars due to their high scalability, extremely light weight, and most importantly large range of fuel options, including those that can be found on Mars or other location throughout the solar system.

   Based on NASA's currently allocated resources for developing advanced propulsion technologies, we will be unable to achieve the 2030 target date. To do so, a dedicated effort will be needed to push these technologies forward. NASA NextSTEP is a good vehicle to do this. To meet the target date would require a follow-on Phase II programs with the all three technologies, MSNW would require a 2 year, $5 M program, followed by a 3 year $25 M program for a lifetime and flight demonstration of a single thruster. In addition, NASA should fund the other two NextSTEP technologies at a minimum of 100 kW per thruster, continue to fund large scale solar panel development at 300 kW, and invest in a large test facility, capable of supporting 100+ kW thruster testing, such as $30 M upgrade to VF-5 at NASA Glenn.

2. To what extent could NASA R&D on in-space propulsion systems benefit commercial industry or other potential users of the technology? What non-NASA applications might be made possible by the technologies we discussed at the hearing?

   Answer: NASA R&D has led the way and opened doors to countless commercial markets, many unforeseen. Investing in in-space transportation technologies are not only a key to sustained exploration of deep space, but will impact all space related technologies, including telecommunication, global monitoring, and defense capabilities. It is also a foundational technology for inventing new markets such as space tourism and asteroid mining. Utilization of advanced ISRU as described by MSNW at the hearing, will open up the entire solar system for NASA, DoD, and others, that will no longer require refueling from Earth. As we increase our capability to move in space, we will build systems and infrastructures that will have large scientific, economic, and security implications for this country.

As shown by the development of all electric spacecraft busses by Boeing and SpaceX, in-space propulsion using electric propulsion is the standard in all emerging commercial satellite systems. This can be directly attributed to NASA's Hall thruster and Ion engine development programs through NASA Glenn and JPL. Clearly, the same benefits apply to DoD spacecraft systems, as shown by the recent AEHF satellite success, where a multi-billion dollar spacecraft was saved solely by Aerojet's Hall Effect Thruster.

3. In your prepared statement you state that "*Of primary importance is the drastic increase in payload mass enabled by high-power EP technology over chemical systems. This increase can amount to nearly three times the delivered payload at high specific impulses.*"
    a. Are there potential applications of this technology for science missions?

       Answer: High-power EP technology will have a profound impact on science missions. Mission designers today are extremely limited in the capabilities of the scientific instruments they are able to send to the outer planets using existing propulsion options. Moreover, extensive R&D dollars are spent to shrink and lighten these instruments. By increasing payload mass fraction, larger, better, and cheaper scientific instruments can be transported to more distant planetary bodies.

    b. How, if at all, could such technology affect the way scientists think about scientific investigations in space?

       Answer: The FRC propulsion technology I discussed allows for us to refuel using in situ resources. By refueling at your destination, instead of having to carry all the fuel for the trip, we can plan return missions that take large samples from other planets back home to Earth. Scientist here on Earth can use instruments and equipment that could never be transported off world to do more science in a day than could be done in decades, forever changing how we research the origins of our solar system and our knowledge of the stars.

4. In planning for the proposed Gateway and Deep Transport space vehicles, NASA will face a major decision on whether these future space vehicles will be propelled using a set of multiple solar electric thrusters or a lesser number of more powerful solar electric thrusters. What key factors should NASA include while conducting a trade-off analysis between these two options? At this point in time, is enough known about each of the options to mitigate projected technical and operational risks? If not, how should that needed knowledge be secured?

   Answer: The key factors NASA should include when conducting a trade-off study of this type are safety, efficiency, and cost. Typically, one-unit systems are the most efficient and effective, which is why we have one engine in our car, not 10 smaller less power engines. Space travel is different than driving down the interstate. Space travel is more akin to intercontinental airplanes which have multiple engines for redundancy and safety. In most mechanical systems 2-4 engines have been shown to be most effective trade-off of cost, efficiency, and safety point of view. Each of the three technologies has advantages. MSNW's FRC propulsion is a highly scalable technology and will have applications for a large range of missions. Optimally three 100 kW engines could make up the propulsion system for 300 kW class missions and one backup thruster, the absolute smallest Mars cargo mission. For future 1 MW class mission, FRC can easy be scaled up to 333 kW each allowing for the same optimal amount of engines to be used.

   Mitigating projected and technical risk can be accomplished by continuing to support early stage innovative research through funding avenues like the SBIR and STTR program. Additionally, encouraging programs like NASA NextSTEP to continually fund an array of technologies will reduce overall risk. By continuing to develop lower technology risk concepts while also maturing lower readiness level technologies we build a robust backbone of capabilities to meet the unforeseen challenges ahead.